EXPERIMENTAL INVESTIGATIONS INTO REPRODUCTION OF PROFILES IN ELECTROCHEMICAL DRILLING

by

Lt. V. RAVINDRANATH

DEPARTMENT OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY KANPUR

FEBRUARY, 1992

EXPERIMENTAL INVESTIGATIONS INTO REPRODUCTION OF PROFILES IN ELECTROCHEMICAL DRILLING

A Thesis Submitted
In Partial Fulfilment of the Requirements
for the Degree of
MASTER OF TECHNOLOGY

by

Lt. V. RAVINDRANATH

to the

DEPARTMENT OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY KANPUR

FEBRUARY, 1992

CERTIFICATE

This is to certify that the work entitled, "Experimental Investigations Into The Reproduction Of Profiles In Electrochemical Drilling" submitted by Lt. V Ravindranath has been carried out under our guidance and has not been submitted elsewhere for a degree.

Dr. V. K. Jain
Assistant Professor,
Dept. of Mech. Engg.,
IIT, Kanpur

Dr. J. L. Batra
Professor,
Dept. of Mech. Engg.,
IIT, Kanpur

ME-1992-M-RAV-EXP

ACKNOWLEDGEMENTS

I would like to express my heartfelt gratitude to my thesis supervisors, Dr. J. L. Batra and Dr. V. K. Jain for their invaluable guidance and constant encouragement through out the present work.

I remain ever thankful to my friends Philip Koshy, Venkata Reddy and A. K. Yadav for their tireless and heartly help extended to me through out my work as and when necessary. Mr. Raghuram, Research Engineer, also warrants a special thanks for his help and advice through out the work.

My sincere thanks are also due to Mr. R. M. Jha and Mr. O. P. Bajaj,Technical Officers, Mr. H. P. Sharma and Mr. P. Gupta for their advice, practical suggestions, co-operation and contribution.

My 'HATS-OFF' to Panigrahi's, Dhar's, Dixit's, Nikita and Anisha for their affection, attachment, concern and support,beyond the scope of imagination and reach of description,because of which my stay at IIT Kanpur has been one of the most enjoyable and memorable one, which I will always miss.

Feb' 92 (Lt. V. Ravindranath)

9010548

CONTENTS

		Page
CERTIFICATE		
ACKNOWLEDGEMENTS		iii
LIST OF FIGURES		vi
LIST OF TABLES		viii
NOMENCLATURE		ix
ABSTRACT		x
CHAPTER1	INTRODUCTION AND LITERATURE SURVEY	
	1.1 Electrochemical Machining (ECM)	1
	1.2 Electrochemical Drilling (ECD)	4
	1.3 Previous Work	5
	1.4 Present Work	7
CHAPTER2	EXPERIMENTATION	
	2.1 Experimental Setup	9
	2.2 Experimental Details	12
	2.3 Variables and Responses	14
	2.4 Design of Experiments	15
	2.5 Plan of Experiments	19
	2.6 Response Surface Equations	26
	2.7 Testing the Homogenity of Variances	28
CHAPTER3	RESULTS AND DISCUSSION	
	3.1 Selection of Set-up, Parameters and their Ranges	31
	3.2 Response Surface Coefficients	33

	3.3 Effect of ECD Paramters on workpiece profile radius	33
	3.4 Discussion	44
CHAPTER4	CONCLUSIONS AND SCOPE FOR FUTURE WORK	
	4.1 Conclusions	62
	4.2 Scope for Future Work	62
REFERENCES		64
APPENDIX		66

LIST OF FIGURES

Figure	Title	Page
1.1	The Electrochemical Machining Process	3
1.2	Schematic Diagram of ECD with Outward Mode of Electrolyte Flow.	3
1.3	A Complete Picture of Various Zones in ECD	6
2.1	Schematic Diagram of Feed Mechanism	11
2.2	Schematic Diagram of Tools	11
2.3	Arrangement for Holding Workpieces	13
2.4	Active Surface of Tool	13
2.5	Photograph of Machined Specimens (Convex Profile Tools)	15
2.6	Photograph of Machined Specimens (Concave Profile Tools)	16
2.7	Photograph of Projection of Reproduced Profiles on the Shadowgraph (Convex Profile Tools)	17
2.8	Photograph of Projection of Reproduced Profiles on the Shadowgraph (Concave Profile Tools)	18
G1	Factor Levels- Tool Radius by Design of Experiments - (Convex Profile Tools)	22
G2	Factor Levels- Tool Radius by Design of Experiments - (Concave Profile Tools)	23

G3	Factor Levels - Input Voltage by Design of Experiments	24
G4	Factor Levels - Feedrate by Design of Experiments	25
A1..A4	Variation of Workpiece Profile Radius with Tool Profile Radius (Convex Profile Tools)	35,36
A5..A8	Variation of Workpiece Profile Radius with Input Voltage (Convex Profile Tools)	40,41
A9..A12	Variation of Workpiece Profile Radius with Feed Rate (Convex Profile Tools)	45,46
B1..B4	Variation of Workpiece Profile Radius with Tool Profile Radius (Concave Profile Tools)	37,38
B5..B8	Variation of Workpiece Profile Radius with Input Voltage (Concave Profile Tools)	42,43
B9..B12	Variation of Workpiece Profile Radius with Feed Rate (Concav Profile Tools)	47,48
C1..C6	Current History (Concave Profile Tools)	56..58
D1..D6	Current History (Convex Profile Tools)	59..61

LIST OF TABLES

Table	Title	Page
2.1	Plan of Experimentation	20
2.2a	Factor Levels - (Designed Values)	21
2.2b	Factor Levels - (Values Achieved for use in Experiments)	21
2.3	Values of Regression Coefficients, Sum of Squares and Analysis of Variance - for Experiments with Convex Profile Tools	29
2.4	Values of Regression Coefficients, Sum of Squares and Analysis of Variance - for Experiments with Concave Profile Tools	30
3.1 & 3.2	Current History (Concave Profile Tools)	50..52
3.3 & 3.4	Current History (Convex Profile Tools)	53..55

NOMENCLATURE

A	Atomic Weight, Kgs
b_o	Regression Coefficient
f	Feed rate, mm/s
G	Grand total of the responses
I	Current, A
k	Number of variables
m	Mass, Kgs
N	Number of Experiments
n_1	Number of repetitive experiments
n_2	Number of non repetitive experiments
x_i	Coded value of variables
y_n	Response
$\bar{y}_1$	Mean of the responses of the central point
y_{1n}	Response of Central Point
y_n	Mean of all the responses
z	Valency
μ	Micro-meter
ECM	Electrochemical Machining
ECD	Electrochemical Drilling
RSM	Response Surface Methodology

ABSTRACT

Electrochemical machining has become one of the most popular methods of unconventional machining in the recent years with the nucleation and growth of very advanced industries, mass manufacturing components, made of difficult to machine materials and very complicated in shape which is a result of the implementation of the principle of minimizing no. of assembled parts in a component/part.

Electro Chemical Drilling (ECD) is a very popular way of drilling holes using ECM process. Nevertheless, this method is preferred to conventional method only when the conventional method remains no longer viable. This is because of a few inherent difficulties which have made commercialisation of this process difficult. Apart from the high initial cost of the machine from which it already suffers, prediction of the anode profile is one of these difficulties hindering the exploitation of this process.

The available literature reveals that the researchers have concentrated their efforts on the work related to profile reproduction in ECD of blind holes using convex profile tools only and have reported some definite relationships between the copied profile radius on the workpiece and the profile radius of the tool used. The relationship between different parameters and copied profile radius on the workpiece can be represented adequately by a second order polynomial model. They have also reported the influence of various process parameters such as mean equilibrium

gap during machining, feed rate, mean electrolyte flow velocity and tool diameter.

The present work is an attempt to extent the previous work to the study of reproduction of profiles in ECD of holes which need not be necessarily blind and the effect of various process parameters on the copied profile radius. Concave tool profiles have also been used to study the reproduction of profiles to be able to have a general idea about the reproduction of any type of profile, since a real life profile is a combinations of various concave and convex profiles. This is also expected to give a fair idea of the influence of flow pattern of the electrolyte past the profile after its exit from the tool tip, on the reproduction of profiles.

Experiments have been plant based on the statistical response surface methodology (RSM). Regression equations correlating the process parameters to the responses have been obtained.

Influence of the process parameters - tool profile radius, feed rate and input voltage on the copied workpiece profile radius have been established and a second order polynomial model was found adequate to represent this relationship.

The pattern of flow of the electrolyte past the profile after its exit from the tool-tip also influences the process itself (mainly stability) and the radius of the copied profile on the workpiece.

CHAPTER 1

INTRODUCTION AND LITERATURE SURVEY

INTRODUCTION

The high pace of technological development has progressively necessiated the use of very special materials with varied properties, in the manufacture of components that would go into the assembly of various machines/equipments which would be subjected to parameters of very high degrees/dimensions in the environment in which they would operate. This also calls for very high and uncompromising standards of dimensional tolerances and surface finish of the components.

The manufacturing cost and time, and the ultimate cost of the product, are of major concern to an industry, besides the quality of the product, to withstand the international stiff market competition. Unconventional machining methods have become increasingly popular [1], wherein difficult to machine materials and mass manufacturing are involved. In certain cases they are the only methods available to solve manufacturing problems of advanced industries using super alloys and other advanced engineering materials.

1.1 ECM

Electro Chemical Machining (ECM) is one of the most widely and successfully used unconventional machining methods [12] which is based on the phenomenon of metal removal by electro chemical dissolution employing an ECM setup with tool as its cathode and work piece as its anode, and a high velocity electrolyte flowing

in between them. Fig. 1.1 gives a schematic layout of a typical ECM set-up.

Electrolytic dissolution of iron in aqueous sodium chloride solution can be considered for purpose of illustration.

When a potential difference is applied across the electrodes, several possible reactions can occur at the anode and the cathode. Certain reactions, however are more likely to take place than the others. Thus preferences can be explained in terms of the energy that is available for each reaction. In the present example of electrochemical dissolution of iron of aqueous solution of Nacl, the probable reactions at the electrodes are as under [3] -

(a) At anode

$$Fe \longrightarrow Fe^{++} + 2e \qquad \text{(Dissolution of iron)} \qquad (1.1)$$

(b) At cathode

$$2H_2O + 2e \longrightarrow H_2\uparrow + 2OH^- \qquad \text{(Generation of hydrogen and production of hydroxyl ions)} \qquad (1.2)$$

The metal ions then combine with the hydroxyl ions to precipitate out as ferrous hydroxide which may further react with water and oxygen to form ferric hydroxide i.e.,

$$Fe + 2H_2O \longrightarrow Fe(OH)_2 + H_2\uparrow \qquad (1.3)$$

$$4Fe(OH)_2 + 2H_2O + O_2 \longrightarrow 4Fe(OH)_3 \qquad (1.4)$$

It may be appreciated that -

1. Since the anode metal (work piece) dissolves electrochemically, according to Faraday's laws of electrolysis, its rate of dissolution depend, only upon its atomic weight A, valency z, the current I, and the time t for which the current passes. Thus the dissolution rate is not influenced by the hardness or any other physical and

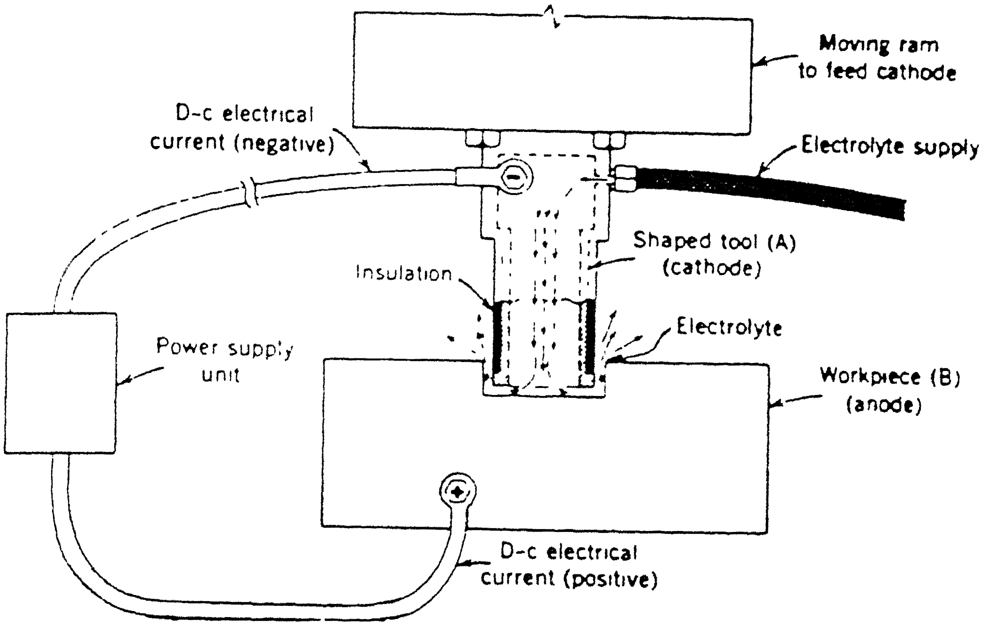


Fig. 1.1 The Electrochemical Machining Process [2]

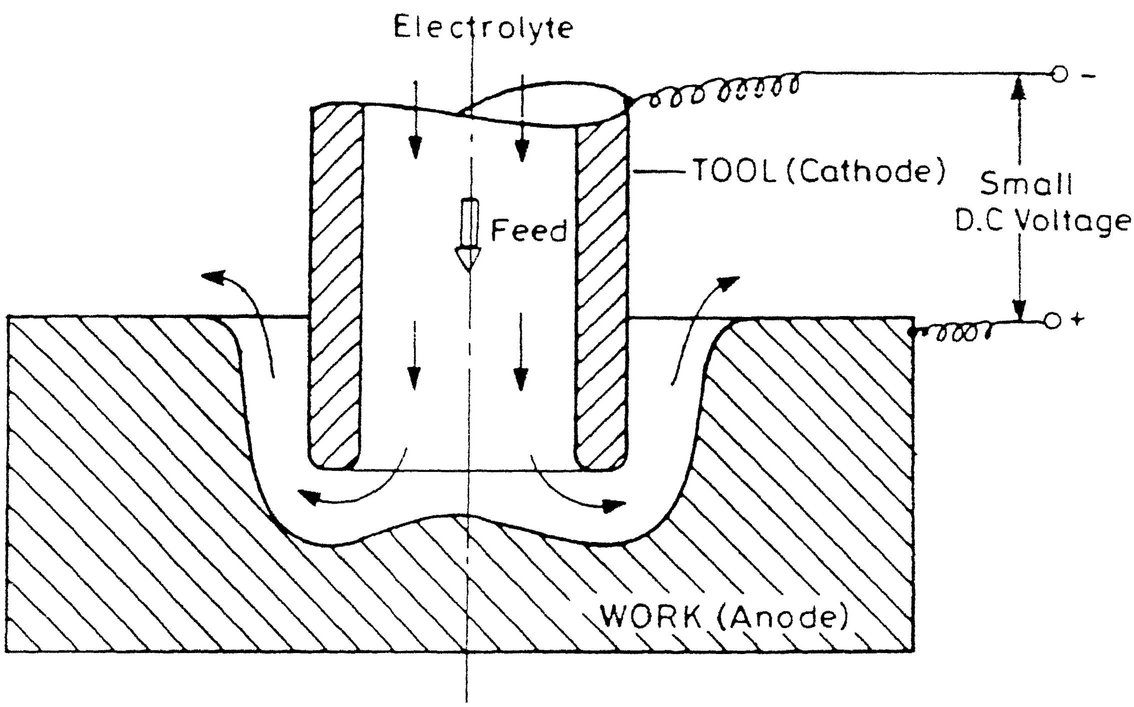


Fig. 1.2 Schematic Diagram of ECD with Outward Mode of Electrolyte Flow

mechanical properties of the work piece material.

2. Since only hydrogen gas is evolved at the cathode, the shape of the electrode remains unaltered during the electrolysis.
3. Electrodes have to be electrically conducting,
4. The removal of metal from the anode is a smooth, gentle process, in complete contrast to the ploughing or smearing action of the conventional machining processes [2].

1.2 Electrochemical Drilling (ECD)

Electrochemical drilling is ECM principle extended to drilling operation, which does have the capabilities of reproducing desired profiles inside a hole.

Electrochemical drilling is a popular way of drilling holes using ECM. As indicated in Fig. 1.2 a tubular electrode is used as the cathode tool. Electrolyte is pumped down the central bore of the tool, which flows out through the side gap formed between the wall of the tool and the hole being drilled in the workpiece. The main machining action is carried out in the interelectrode gap (IEG) formed between the leading face of the drill-tool and the base of the hole in the workpiece. ECM also proceeds laterally between the side walls of the tool and the component. Since the lateral gap width is much larger than that at the leading face of the tool the machining rate in the sides is much lower. The overall effect of the side ECM is to increase the diameter of the hole that is produced. A wide range in hole sizes can be drilled, diameters as small as 0.05mm to as large as 20mm have been reported [2]. Length/diameter ratio upto 20:1 can be accomplished.

Under ideal conditions ECM is capable of producing tolerances of approximately ± 0.012mm, although shop floor reality is closer to ± 0.05mm. The typical overcut at the side of the tool is approximately 0.12mm. Surface finish is dependent on the workpiece material, the type of the tool used, the electrolyte flow, and the current density. Usually the surface finish at the tip of an ECM tool will be 0.1–0.15µm. The side of the tools may produce surface finishes as rough as 5µm because of low current density [2].

No detrimental effects on materials have been found with ECM when parameters are properly selected.

Fig. 1.3 shows the typical cross-section of a circular hole produced by a cylindrical tool in ECD.

The anode profile thus generated has been divided on the basis of electrolyte flow into four distinct regions, i.e. stagnant, front, transition and side [12,6].

Applications –

In gas turbine industries, it is extensively used for drilling the cooling holes in gas turbine blades and for many other jobs in the manufacture of gas turbine engines. Shaped holes without burrs can be pierced in thin workpieces. In the electronics industry ECM is used for cutting thin sheets of silicon or germanium. Process also finds extensive application in aerospace and nuclear engineering fields [12].

1.3 Previous Work

Some work has been carried out in the field of corner reproduction accuracy in ECD of blind holes [12]. Some of their

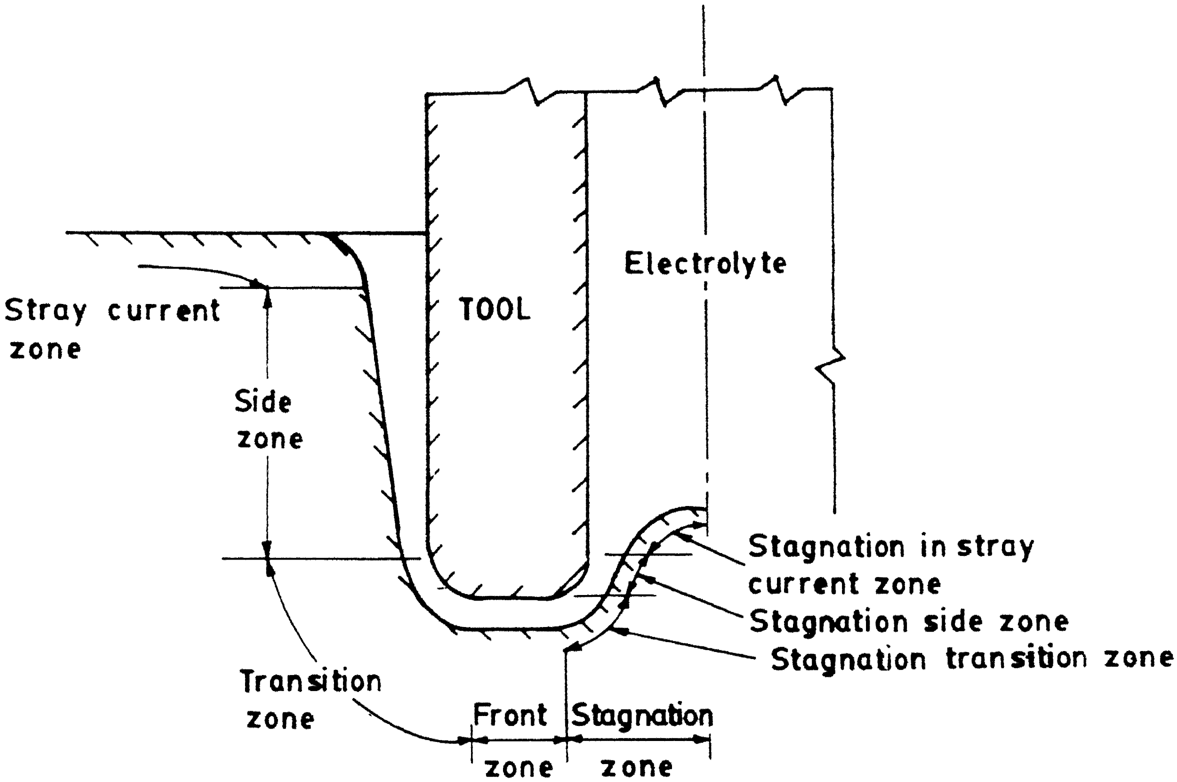


Fig. 1.3 A Complete picture of various zones in ECD

findings are as follows:

(a) A relation of the type -

$$r_a = A\, e^{B.r_c} \quad (\text{for } r_a > 0) \qquad (1.5)$$

between the corner radii of anode r_a and cathode r_c is satisfactory in most cases. A & B are constants specific to working conditions

(b) In majority of the cases, the corner radius of the anode (work piece) is greater than that of the corner radius of the cathode (tool) i.e. $r_a > r_c$

(c) the relationship between the radius of the profile reproduced on the work piece and that of the tool is also dependent upon the mean equillibrium gap during machining, feed rate, mean electrolyte flow velocity and the tool diameter.

(d) a second order polynomial model adequately represents the relationship between the ECM process parameters such as electrolyte conductivity, initial interelectrode gap, feed rate, tool corner radii and diameter of the tool, and

(e) the surfaces reproduced are quite smooth.

1.4 Present Work:

All the investigations reported in the available literature have been carried out exclusively for reproduction of corner radius for a convex type of profile in blind holes. In the present work, an attempt has been made to extend the previous work to a more generalized case i.e.,profile/contour reproduction in holes, not necessarily perfectly blind. Such holes are likely to be encountered in die casting dies having riser, runners and gates. Here it is assumed that the profile is a combinations of a

few convex and concave profiles put together in series. Experiments have been carried out also using concave profiles to study the reproduction of profiles in ECD which would also reveal the influence of the pattern of flow of electrolyte after its exit from the tool tip on the profile reproduction.

CHAPTER 2

EXPERIMENTATION

2.1 Experimental Setup:

A single station MICO-BOSCH electro chemical deburring machine modified to suit the electro chemical drilling operation was used. The deburring machine used is an industrial special purpose machine designed and fabricated to meet specific requirements of deburring MICO fuel pump shaft, with a number of built in safety cut off devices to prevent erraneous/careless operation of the machine and thus prevent an accident resulting in damage to men, machine or the job.

The machine is capable of supporting a maximum process current of 600 A with a facility of increamenting input voltage by 2 volts in 8 steps begining with 12 volts. It has an electrolyte tank of 1000 litres capacity with baffles provided to minimise sludge reaching the coarse and fine filters of the pump suction. The electrolyte is pumped at a constant pressure of 4.5 bars. A pressure regulator provided at the pump discharge side maintains a constant pressure of 4 bars (approx.) for the operation. A pneumatic actuator clamps the fixture within which a batch of 8 jobs to be simulataneously deburred are placed, the stroke of which can be adjusted. A timer provided cuts off the process at the end of the set time, the maximum process time that can be set being 03 minutes.

Modifications:

The MICO fuel pump fixture at the lower end of the pneumatic

actuator was replaced by a constant tool feed mechanism which translates the rotary motion of a stepper motor shaft into axial to and fro motion of a slide using a lead screw and a nut type arrangement as shown in Fig.(2.1). The tool holder push-fits at the end of the slide and the tool in turn push-fits in the tool holder. The electrolyte is supplied through a central hole in the tool. The D.C. power (low voltage, high amperage) is supplied between the tool and anode. The mechanism is capable of a total of 24mm vertical traverse.

A stepper motor control unit was used to obtain the required feed rate. It has the following features:

(a) A 16 key keyboard to enable program the auto feed mechanism specifying in sequence-

1) no. of steps

2) idle time before start of feed

3) time per step

4) half/full step

5) direction of feed (forward/reverse)

or manual feed in either directions.

b) A 4 digit display indicating mode of opeation (auto/manual) and number of steps incremented.

c) Total traverse of 24 mm of the mechanism is executed in 2400 steps with vertical traverse of 0.01 of a mm in a step.

d) The control unit is designed for

1) a maximum of 9999 steps

2) a maximum of 30 millisecs/step.

The timer was bipassed to enable continuous machining.

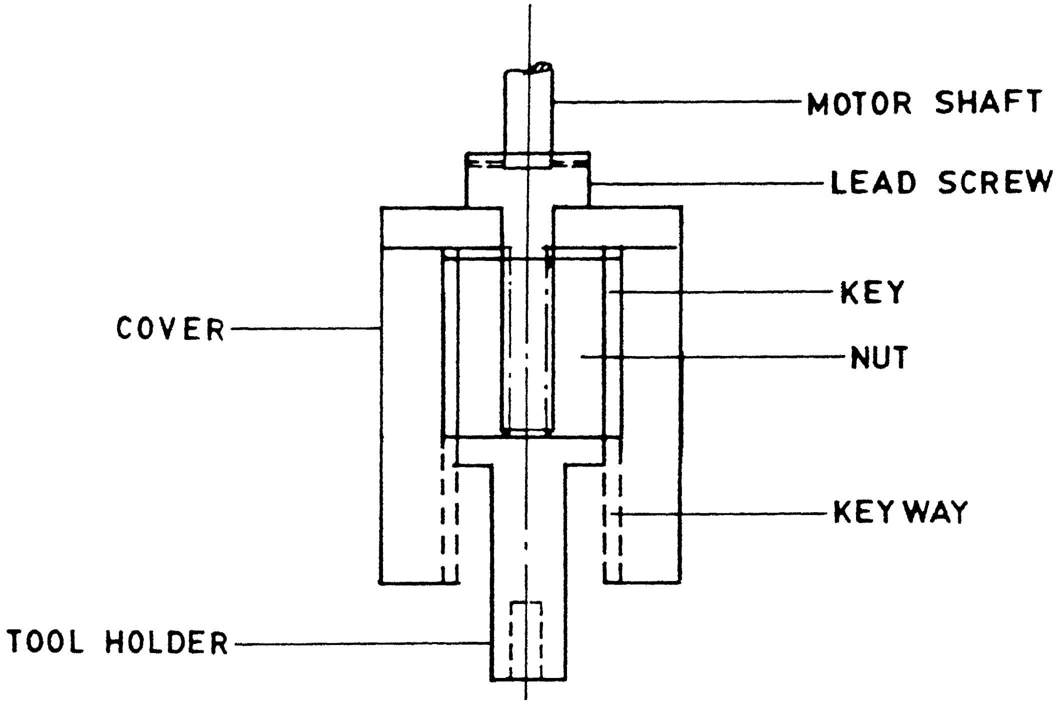


FIG. 2.1 Schematic diagram of feed mechanism

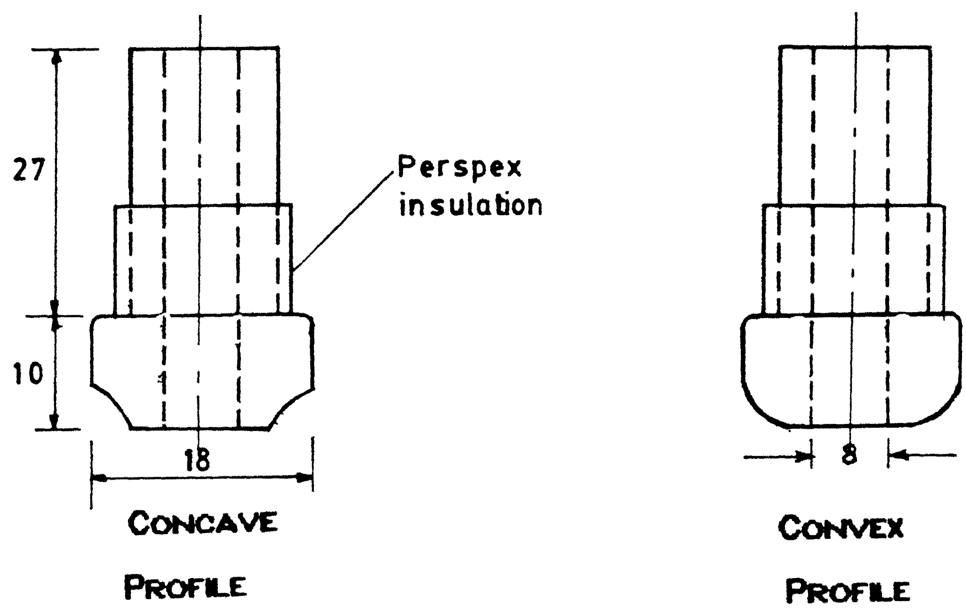


FIG. 2.2 Schematic diagram of tools

2.2 Experimental Details:

Experiments were planned in accordance to design of experiments. The specifications of the tool, workpiece and the electrolyte used are as follows-

TOOL:

Well finished tubular bit type of tools made of brass with a length of 10 mm, dia of 18 mm, bore of 08 mm were used as shown in Fig. (2.2). The experiments were conducted in two different sets using concave and convex radii used corner tools. The electrolyte was pump through the tool and the tool which received electrical supply at the tool holder end was insulated from the rest of the system Fig.(2.4).

WORKPIECE:

HSS bars of 16 mm square cross section, with surfaces thoroughly ground and cleaned were used. The workpieces were held in an insulated vice and the power supply terminal connected to one of its ends using a clamp as shown in fig.(2.3).

ELECTROLYTE:

Sodium Chloride solution in water was used as the electrolyte. Its specifications are

Specific gravity = 1.17

Conductivity = 0.02 ohm^{-1} mm^{-1}

pH value = 7.45 at room temperature of 22°celsius

Pressure = 4 bars

Flow rate = 1.9 x 10^{-4} m^3/sec

Conductivity and pH value were monitored using digital conductivity and pH meters and their values were maintained

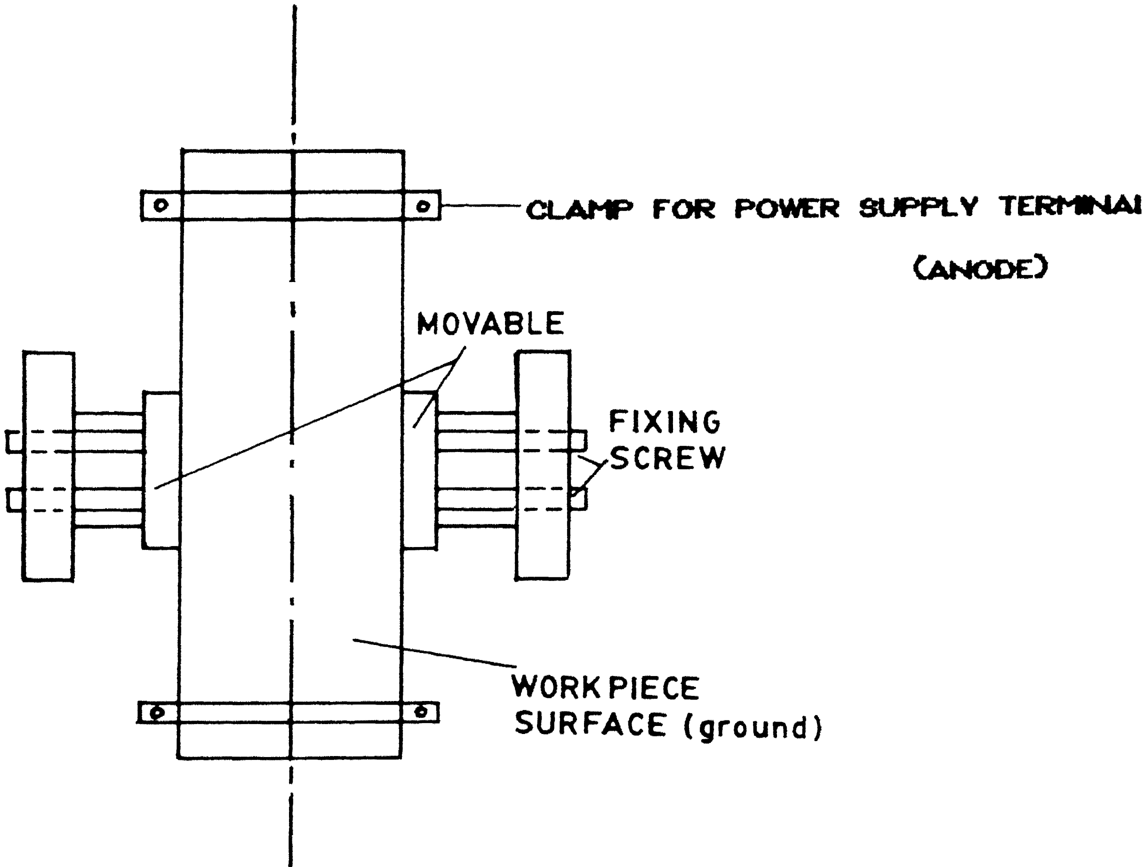


FIG. 2.3 Arrangement for holding the workpiece

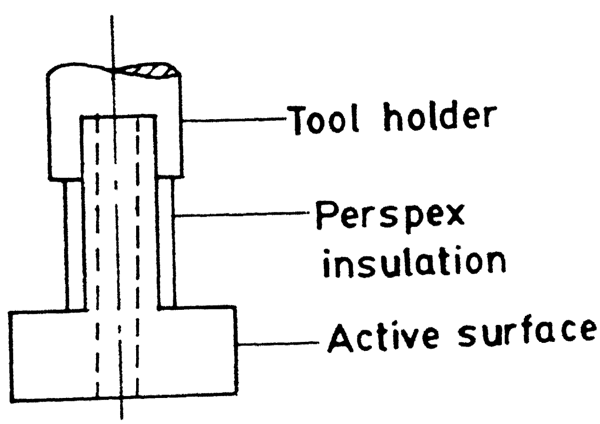


FIG. 2.4 Active surface of tool

constant.

2.3 Variables and Responses:

SELECTION:

Tool end corner profile radius (x1), input voltage (x2), and feed rate (x3) were considered as the controllable variables to study their effects on the reproduction of profiles on the workpiece. Machining was carried out to a depth of 10 mm in all the cases.

MEASUREMENT:

The tools were machined on a NC-lathe to obtain the required magnitude of the radius of the profiles and were measured on the shadowgraph. The values of 'c' and 'h' were read out from the shadowgraph scales which have a least count of 1 micron where,

c = length of the chord

h = length of the perpendicular to the chord from the tangent to the curve through the point of intersection.

The radius was calculated using the relation [12]:

$$r = \frac{c^2 + 4h^2}{8h} \qquad (2.1)$$

The mean radii reported here was obtained as the average of three different values. In case 'h' is measured at different points on the circumference of the tool. The radius of the profile reproduced on the workpiece after drilling, was measured by replica technique using plastic replica kit, the material of which is supposed to have very minimal shrinkage. The radii were calculated using the relation 2.1. For each workpiece two sets of

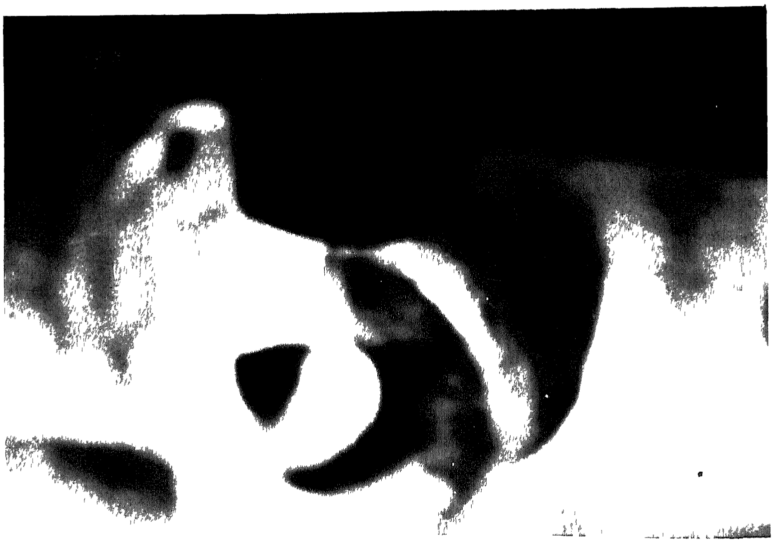
observations for 'h' and 'c' were measured using the shadowgraph and were used to obtain the average value of 'r'. Photographs in Fig. 2.5 and 2.6 show few of the machined specimens and in Fig.2.7 and Fig.2.8, the projection of few of the reproduced profiles obtained by replica technique, on the shadowgraph.

2.4 Design of Experiments:

The experimental work carried out to study the effects of different variables on the responses is planned in accordance with the statistical technique of experimental design. According to Adler, Markova and Gravosky [7] the design of an experiment is the procedure of selecting the number of trials and conditions for running them, essential and sufficient for solving the problem that has been set with the required precision. The following features are of great importance,

1) Striving to minimize the total number of trials,
2) The simultaneous variation of all the variables determining a process according to special rules called algorithms,
3) The use of a mathematical apparatus formalizing many actions of the experimenter and
4) The selection of a clear cut strategy permitting the experimenter to make substantial decisions after each series of trials or experiments.

The problem for whose solution the design of experiments can be used are exceedingly diverse. With a well designed experiment it is possible to determine accurately, with much less effort, the effect of change in one variable on the process output (also known as the response or yield) and the interaction effect between the

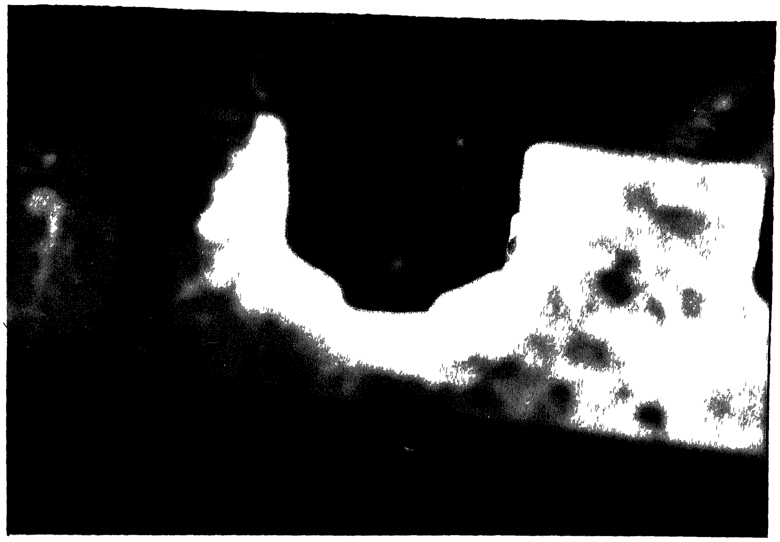


EXPT. CODE - C2

EXPT. CODE - E8

FIG.2.5: PHOTOGRAPH OF MACHINED SPECIMENS

(CONVEX PROFILE TOOLS)



EXPT. CODE – C3

EXPT. CODE – C4

FIG.2.6: PHOTOGRAPH OF MACHINED SPECIMENS

(CONCAVE PROFILE TOOLS)

EXPT. CODE - C1

EXPT. CODE - D2

EXPT. CODE - E2

FIG.2.7: PHOTOGRAPH OF PROJECTIONS OF REPRODUCED PROFILES ON THE SHADOWGRAPH (CONVEX PROFILE TOOLS)

EXPT. CODE – A1

EXPT. CODE – C4

EXPT. CODE – C1

FIG.2.8: PHOTOGRAPH OF PROJECTIONS OF REPRODUCED PROFILES ON THE SHADOWGRAPH (CONCAVE PROFILE TOOLS)

different factors if any. If all the investigated factors are quantitative in nature, then it is possible to approximate the response y_n as a polynomial equation.

$$y_n = b_o + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i<j} b_{ij} x_i x_j \qquad (2.2)$$

where x_i (i=1,2,.....k) are coded levels of k quantitative variables and b_o, b_1 etc are the least square estimates of the regression coefficients. The polynomial in the above equation is also known as regression function and the first term under the summation sign pertains to linear effects, the second term under the summation sign pertains to quadratic effects and the third term pertains to interaction effects of the investigated parameters. From the initial experiments it was observed that the linear model is not adequate. Since the F-ratio of second order design lies within the stipulated value, a second order polynomial equation is selected here.

2.5 Plan of Experiments:

It was decided to study the influence of three independent variables mentioned in Section 2.3 of this chapter. In order to study the effects a second order polynomial surface equation (2.2) as above is adopted [8].

To estimate the values of the coefficients, in equation (2.2) a central composite rotatable design was employed. The plan of the experimentation is described in Table 2.1 and the selection of the factor limits was done as per Table 2.2(a) while the actual values of parametes that could be achieved for use in the experiments are reflected in Table 2.2(b) because of the practical

Table 2.1

Plan of Experimentation

Central Composite rotatable second order designs

3 x variables N = 20 treatment combinations

Sl. No.	Expt. Code	Variables			Responses [w/p radius in	
		Tool Radius x_1	Input Voltage x_2	Feed rate x_3	Convex	Concave
1	C2	−1	−1	−1	2.218	2.671
2	D2	1	−1	−1	5.132	8.314
3	C3	−1	1	−1	2.942	2.384
4	D4	1	1	−1	4.095	4.980
5	C1	−1	−1	1	2.915	10.436
6	D1	1	−1	1	4.753	3.664
7	C4	−1	1	1	2.55	4.070
8	D3	1	1	1	5.148	4.959
9	A1	−1.682	0	0	1.672	2.337
10	B1	1.682	0	0	6.248	17.522
11	E1	0	−1.682	0	3.457	4.436
12	E2	0	1.682	0	4.482	5.599
13	E3	0	0	−1.682	3.805	3.607
14	E4	0	0	1.682	4.436	9.328
15	E5	0	0	0	3.222	6.985
16	E6	0	0	0	3.120	4.096
17	E7	0	0	0	3.843	8.064
18	E8	0	0	0	3.235	4.813
19	E9	0	0	0	2.842	7.232
20	E10	0	0	0	3.979	7.325

Table 2.2(a)

Factor Levels

Variables	Levels	-1.682	-1	0	1	1
Tool radius (in mm) (x1)	convex	1.58	2.45	3.70	4.97	5
	concave	2.6	3.42	4.6	5.75	6
Input Voltage (x2)		12	13.65	16	18.35	2
Feed rate (in mm/min) (x3)		0.5	0.64	0.845	1.055	1

Values as per design of experiments
(refer Fig. G1, G2, G3, G4)

Table 2.2(b)

Factor Levels

Variables	Levels	-1.682	-1	0	1	1.
Tool radius (in mm) (x1)	convex	1.58	2.808	3.73	5.048	5.
	concave	2.6	3.55	4.72	5.66	6.
Input Voltage (x2)		12	14	16	18	20
Feed rate (in mm/min) (x3)		0.5	0.67	0.85	1.03	1.

Parameters that could be achieved
for use in the experiments

x – VALUES ACHIEVED FOR USE IN EXPTS.

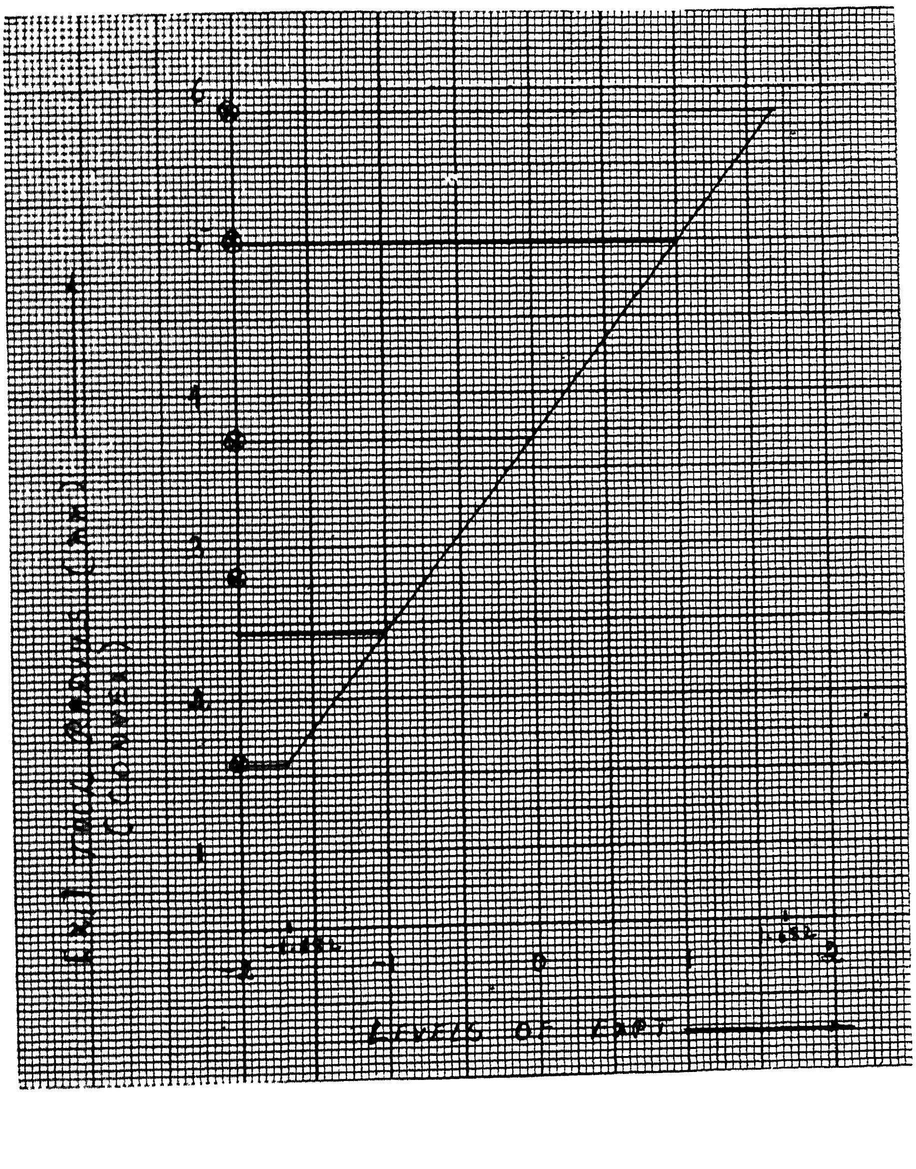


FIG. G1. FACTOR LEVELS – TOOL RADIUS, BY DESIGN OF EXPTS.

(CONVEX PROFILE TOOLS)

x – VALUES ACHIEVED FOR USE IN EXPTS.

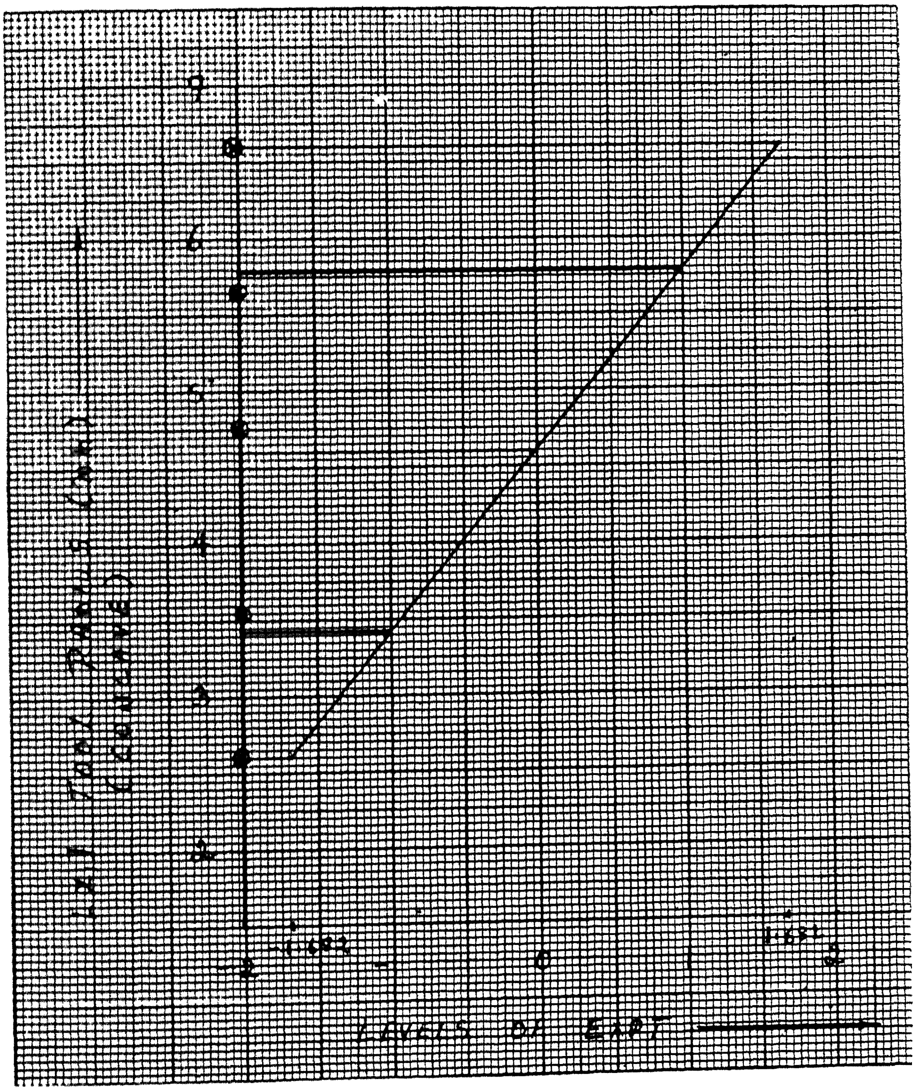


FIG. G2. FACTOR LEVELS – TOOL RADIUS, BY DESIGN OF EXPTS.

(CONCAVE PROFILE TOOLS)

x – VALUES ACHIEVED FOR USE IN EXPTS.

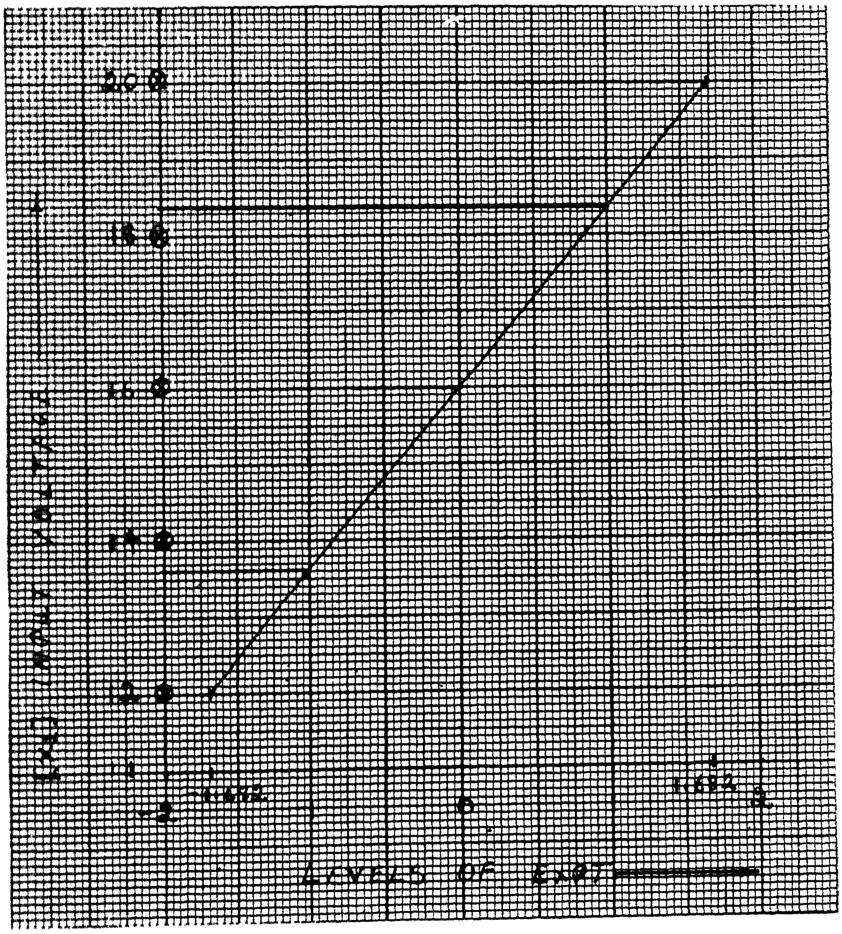


FIG. G3. FACTOR LEVELS – INPUT VOLTAGE, BY DESIGN OF EXPTS.

x – VALUES ACHIEVED FOR USE IN EXPTS.

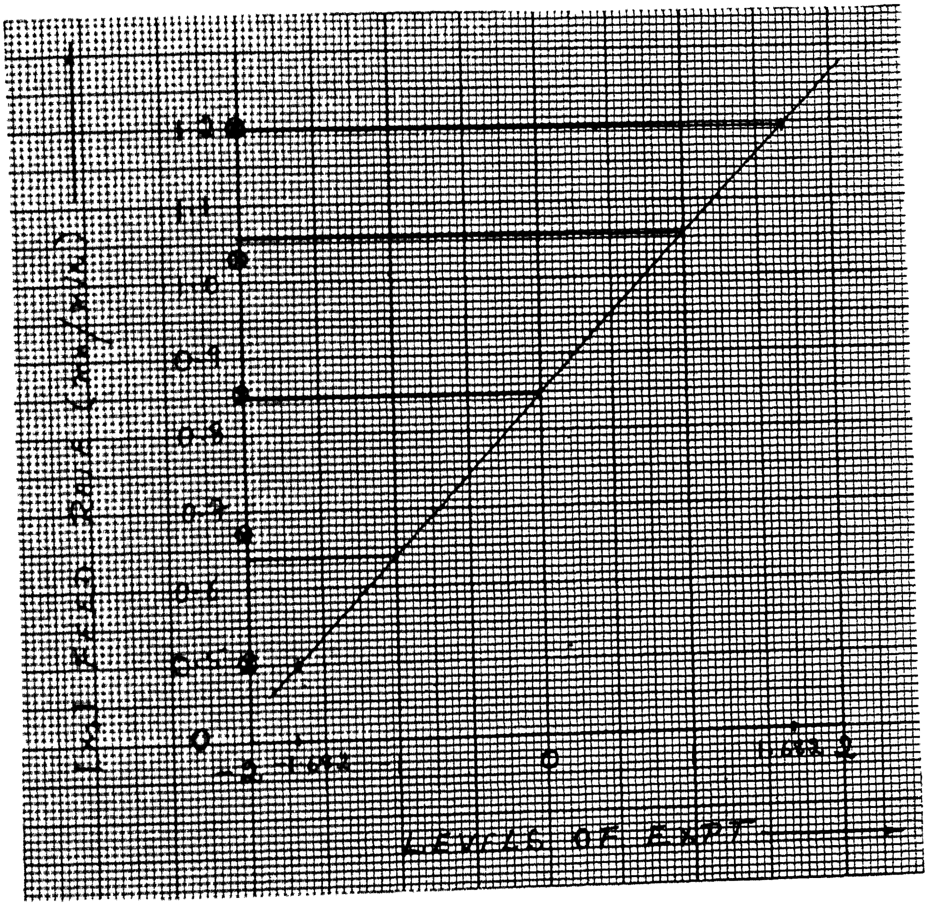


FIG. G4. FACTOR LEVELS – FEED RATE, BY DESIGN OF EXPTS.

limitations.

2.6 Response Surface Equations:

A mathematical model for the second order response surface would be of the following form

$$y = b_o + b_1 x_1 + b_2 x_2 + b_3 x_3 + b_{11} x_1^2 + b_{22} x_2^2 + b_{33} x_3^2 + b_{12} x_1 x_2 + b_{13} x_1 x_3 + b_{23} x_2 x_3 \qquad (2.3)$$

where y is the response, $x_1 \ldots\ldots x_3$ are the process parameters and b_o, $b_1 \ldots\ldots b_{23}$ are the coefficients to be calculated.

Twenty simultaneous equations were obtained from the design matrix (Table 2.1) and these were represented in matrix form as

$$[y]_{20\times1} = [x]_{20\times10}[b]_{10\times1} \qquad (2.4)$$

where [y] is the response matrix, [x] is the matrix of variables and [b] is the matrix of coefficients. The least square estimates of the [b] coefficients were determined by

$$[b] = \left[[x^T][x]\right]^{-1} [x]^T [y] \qquad (2.5)$$

Making use of this equation, the coefficients for the model were calculated. A software programme using NAG subroutines was developed which is given in Appendix 1.

The analysis of variance was carried out for each of the responses separately [8]. In the analysis of variance it is usually of interest to partition the sum of squares of the y's into the contribution due to the first order terms, the additional contribution due to the second order terms, a lack of fit component which measures the deviations of the responses from the

fitted surface and finally a measure of the experimental errors obtained from the replicated points at the centre. General formulae for the sum of square are as follows:

	Sum of Squares	Degrees of freedom
Ist Order Terms:	$\sum_{i=1}^{k} b_i(iy)$	k
IInd Order Terms:	$b_o(Oy)+\sum_{i=1}^{k} b_{ii}(iiy)+\sum_{i<j} b_{ij}(ijy)-G^2/N$	$k(k+1)/2$
Lack of fit:	found by subtraction	$n_2-k(k+3)/2$
Experimental error:	$\Sigma(y_{1u} - \bar{y}_1)^2$	$n_1 - 1$
Total	$\sum_{u=1}^{N} y_u^2 - G^2/N$	n_1+n_2-1

where,

b_i, b_{ii}, $b_{ij\,(i<j)}$ – Regression Coefficients

i_y, ii_y, $ij_{y\,(i>j)}$ – sum of squares

G – Grand Total (Total of sum of squares)

N – No. of experiments/combinations

Y_{1u} – Measured responses of experiments repeated

$\bar{Y}_{1u}$ – Mean of measured responses of experiments repeated

Y_u – Measured responses of each of the experiments of N combinations

k – No. of variables measured

n_1 – No. of experiments repeated

n_2 – No. of experiments not repeated

Accordingly the values of the regression coefficients, their sum

of squares (s.s) and the analysis of variance (ANOVA) for two sets of responses (convex and concave profiles) are given in Table 2.3 and 2.4.

2.7 Testing the Homogenity of Variances

The homogenity of variances is tested with the aid of various statistical data. The simplest of them is the Fisher ratio (F ratio) designed for comparing two variances. The *F ratio is the ratio of mean sum of squares (m.s) due to lack of fit to the mean s squares due to experimental errors*. The value obtained is compared with the tabulated value of the F-ratio [8].

If the F-ratio obtained for variances is greater than the tabulated value for the corresponding degrees of freedom and the selected significance level, this means *that the variances significantly differ from each other i.e, they are not homogeneous*.

Here also the F-ratio has been calculated for the the models and they are found to be within 95% confidence limits.

For the convex profile model

$$\text{F-ratio} = \frac{0.31439}{0.1951} = 1.61143$$

For the concave profile model

$$\text{F-ratio} = \frac{2.0806}{19.3822} = 0.10734$$

Since all the F ratios are far less than $F_{0.05,6,5} = 4.95$ the models are found to be adequate within 95% confidence limits.

Table 2.3

Regression Coefficients, Sum of Squares and Analysis of Variance - Workpiece Profile Radius - Expts. with Convex Profile Tools

Values of Regression Coefficients		Sum of Squares	
b_0	3.384	(0y)	74.0990
b_1	1.186	(1y)	16.1948
b_2	0.106	(2y)	1.4461
b_3	0.150	(3y)	2.0453
b_{11}	0.136	(11y)	52.1647
b_{22}	0.140	(22y)	52.2184
b_{33}	0.193	(33y)	53.0728
b_{12}	-0.126	(12y)	- 1.0060
b_{13}	0.046	(13y)	0.3640
b_{23}	0.043	(23y)	0.3480
Grand Total (G)			250.9471

ANOVA

	S.S	D.F	M.S
First order terms	19.6671	3	6.5557
Second order terms	-2873.1649	5	-478.8608
Lack of fit	1.8863	6	0.31439
Error	0.9759	5	0.1951
Total	-2850.6356	19	

Table 2.4

Regression Coefficients, Sum of Squares and Analysis of

Variance - Workpiece Profile Radius -

Expts. with Concave Profile Tools

Values of Regression Coefficients			Sum of Squares
b_0	6.483	(0y)	122.8220
b_1	2.047	(1y)	27.8972
b_2	-0.493	(2y)	-6.7358
b_3	1.055	(3y)	14.4027
b_{11}	0.820	(11y)	97.6616
b_{22}	-0.917	(22y)	69.8683
b_{33}	-0.404	(33y)	78.0727
b_{12}	0.577	(12y)	4.6140
b_{13}	-1.765	(13y)	-14.1220
b_{23}	-0.181	(23y)	- 1.4500
Grand Total (G)			393.0307

ANOVA

	S.S	D.F	M.S
First order terms	75.5095	3	25.1698
Second order terms	-6915.0796	5	-1383.0159
Lack of fit	12.4837	6	2.0806
Error	96.911	5	19.3822
Total	-6730.1754	19	

CHAPTER 3

RESULTS AND DISCUSSION

A second order polynomial model adequately represents the relationship between ECD process parameters such as tool profile radius, input voltage and feed rate, and the copied profile radius on the workpiece.

3.1 Selection of Set-up, Parameters and their Ranges:

One of the goals of any research work is normally to have its results input into industries, wherein the concept, visualisation and efforts are actually translated into instruments of actual utilization that benefit mankind. This was kept in mind while making choice of the set-up, parameters and the ranges.

ECD SET-UP:

Keeping the above in view, the Mico-Bosch machine which is currently in use in Mico, Bangalore for the purpose of deburring fuel pump shops was selected to carry out the experiments, as electro chemical deburring is similar to ECD except in that the feed rate is zero.

ELECTROLYTE:

Sodium chloride solution with specifications mentioned in Section 2.2 of Chapter 2 was selected to bring the laboratory conditions more close to the industrial working environment/shop floor conditions, since the same is in use at Mico, Bangalore. Above all, it is cheap, commonly used and easily available electrolyte. Therefore, it is industrially more viable.

ELECTRODE MATERIALS:

a) TOOL: Brass was selected as the tool material, keeping in view its reasonable cost, machinability and availability.

b) WORKPIECE: HSS was as the workpiece material. It may be pointed out that the ECM is gaining popularity for machining difficult to machine materials although, it is a well established fact that the physical and mechanical properties of the workpiece material do not influence the ECM process. An attempt was also made to obtain the materials from HAL, Kanpur (Turbine Blade material) and Ordnance Gun Factory, Kanpur, but since the material was not available in the form and quantity, that was required for experiments, HSS was chosen due to its ease of availability and reasonable costs.

PARAMETERS AND THEIR RANGES:

The physical design and construction of the experimental setup and the electrolyte used imposed restrictions to the ranges of different parameters.

INPUT VOLTAGES AND FEED RATES:

o The input voltages could be selected in 8 steps with a difference of 2 volts between each starting 12 volts. Selection of the maximum voltage and feed rate were guided by the ability of the process to sustain without shorting and sparking continuous machining drilling during experiments.

o The used values of minimum feed rate and voltage were selected since the machine has a built in cut-off to trip the machine and interrupt the process in the event of very low loads of process current for a short time.

o TOOL PROFILE RADIUS: The minimum tool profile radius was selected keeping in view the difficulties that would be encountered in the measurement of the tool profile as well as the copied profile.

o There are no provisions on the machine tool to change the flow rate of the electrolyte and the process current.

3.2 Response Surface Coefficients:

Making use of the equation for the response (equation 2.3) the regression coefficients were calculated for convex and concave profiles. For this purpose a computer program was developed using NAG subroutines from the NAG library which is placed at Appendix 4. The values of the regression coefficients are shown in Tables 2.3 and 2.4 together with their sum of squares.

The analysis of variance (ANOVA) was carried out for each of the models. The adequacy of the models were tested by evaluating the F coefficients. Since the F-ratios are less than the tabulated value of $F_{0.05,4,5}$ =4.95, the models are found to be adequate within 95% confidence limits.

3.3 Effect of ECD Parameters on Workpiece Profile Radius:

The analysis holds good for the chosen range of values of parameters within which the experiments were conducted [Table 2.2- A and B].

A. Effect of Tool Profile Radius (x1) on Workpiece Profile Radius:

a) CONVEX TOOL PROFILE:

o For *constant feed rate* (x3)-

The workpiece profile radius obtained increases as the of the

input voltage (x2), increases for all the chosen tool profile radii as shown in [Fig. A1 and A2].

o For *constant Input Voltage* (x2)-

The copied workpiece profile radius again increases with the tool profile radius, for any value of feed rate (x3) as shown in [Fig. A3 and A4].

b) CONCAVE TOOL PROFILE:

o For *constant Feed Rate* (x3)-

As can be seen, no particular trend is exhibited by the curves since, for a feed rate of x3 = -1.0 (coded values) the workpiece profile radius increases with the increase in tool profile radius for different chosen values of input voltages (x2) while for x3 = 1.0 the workpiece profile radius decreases with an increase in tool profile radius upto a certain value and then increases, for all chosen value of input voltage (x2) as shown in [Fig. B1 and B2].

o For *Constant Input Voltage* (x2)-

The copied workpiece profile radius increases continuously with an increase in tool profile radius for values of input voltages (x2) upto 0.0 (coded values) while for values of x2 above 0.0 the workpiece profile radius decreases upto a certain value of the tool profile radius chosen and then increases as shown in [Figs. B3 and B4).

o The trends exhibited by these curves are totally different from those exhibited by curves obtained with convex profile tools.

B. Effect of Input Voltage on Workpiece Profile Radius:

a) CONVEX TOOL PROFILE:

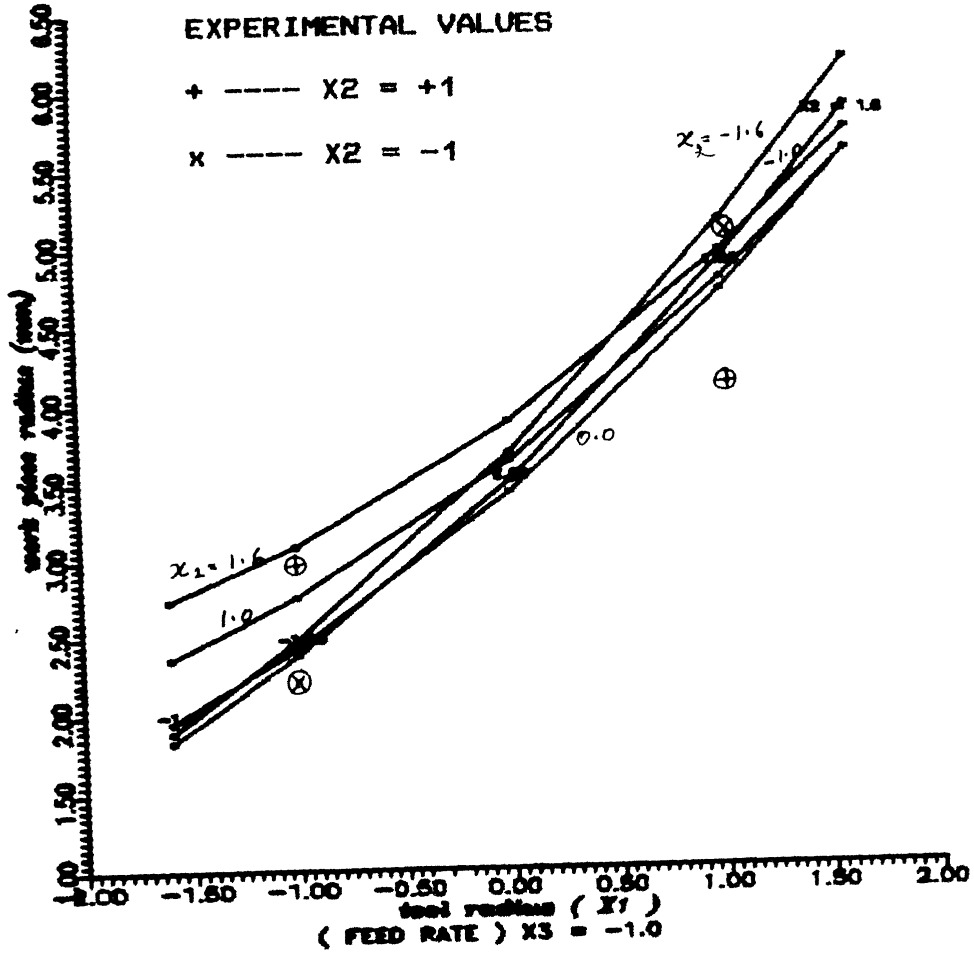


FIG. A 1

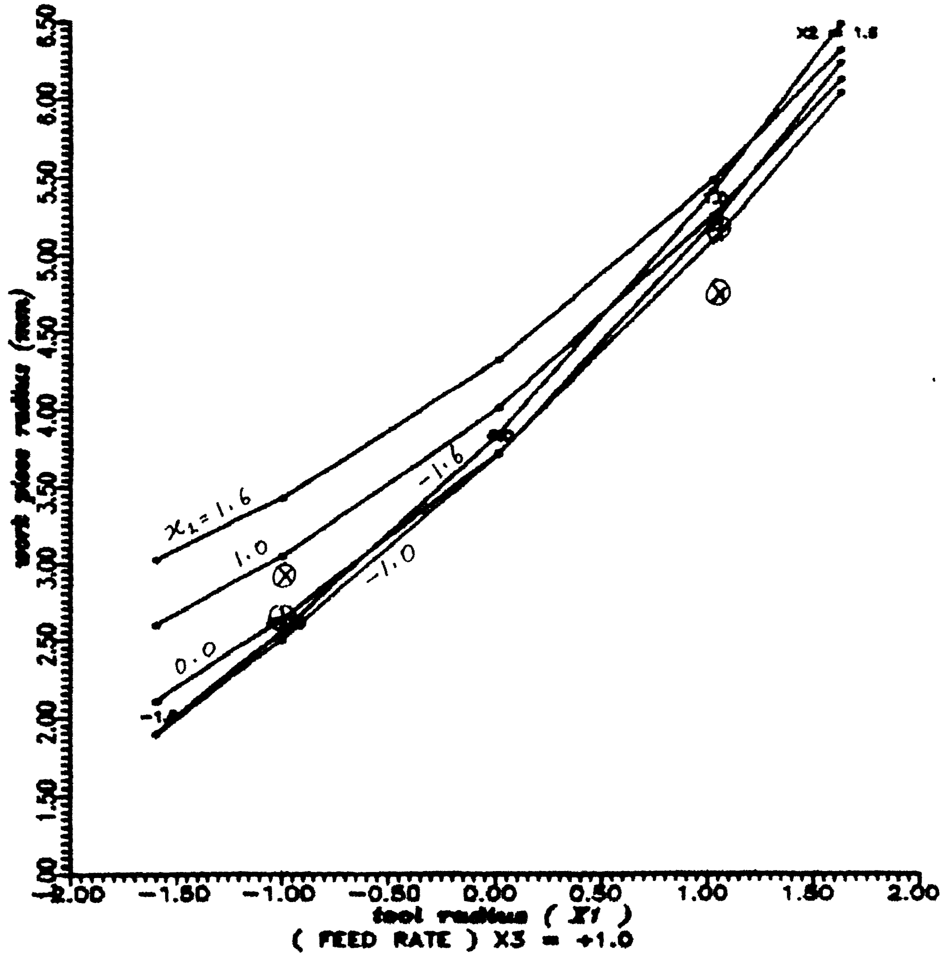


FIG. A 2

VARIATION OF WORKPIECE PROFILE RADIUS WITH TOOL PROFILE RADIUS

(CONVEX PROFILE TOOLS)

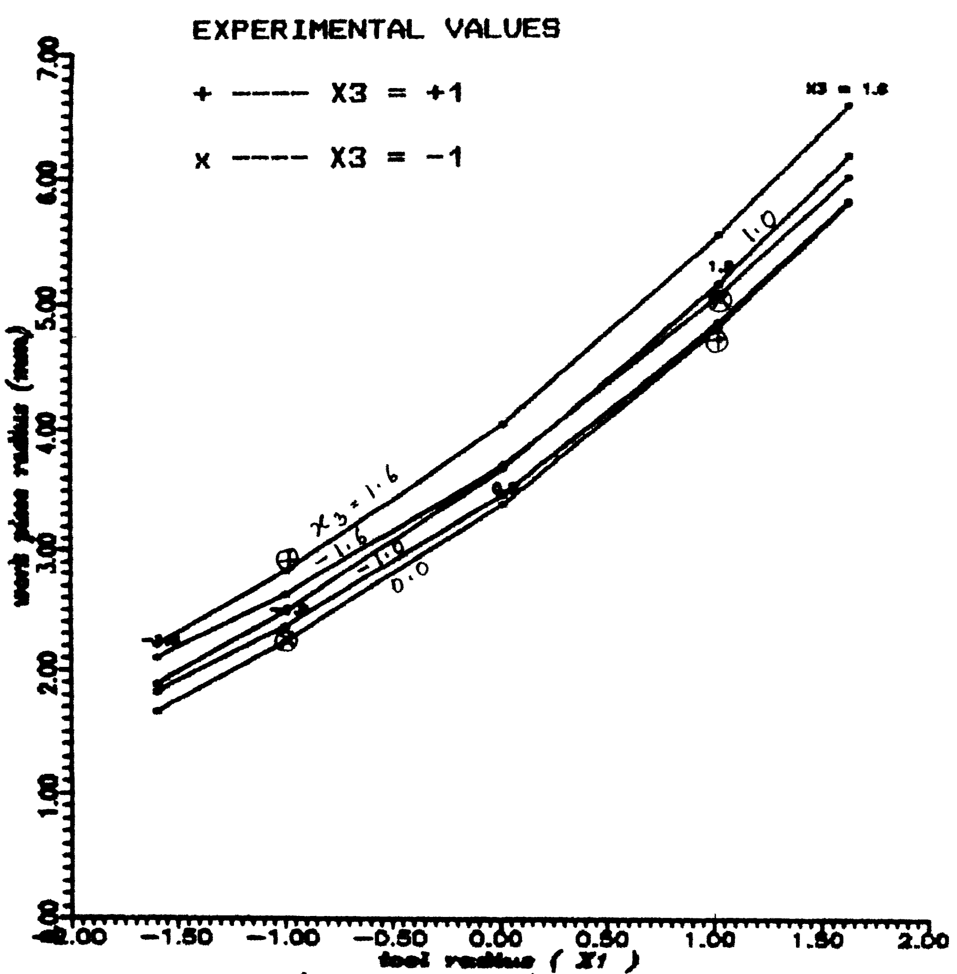


FIG. A 3

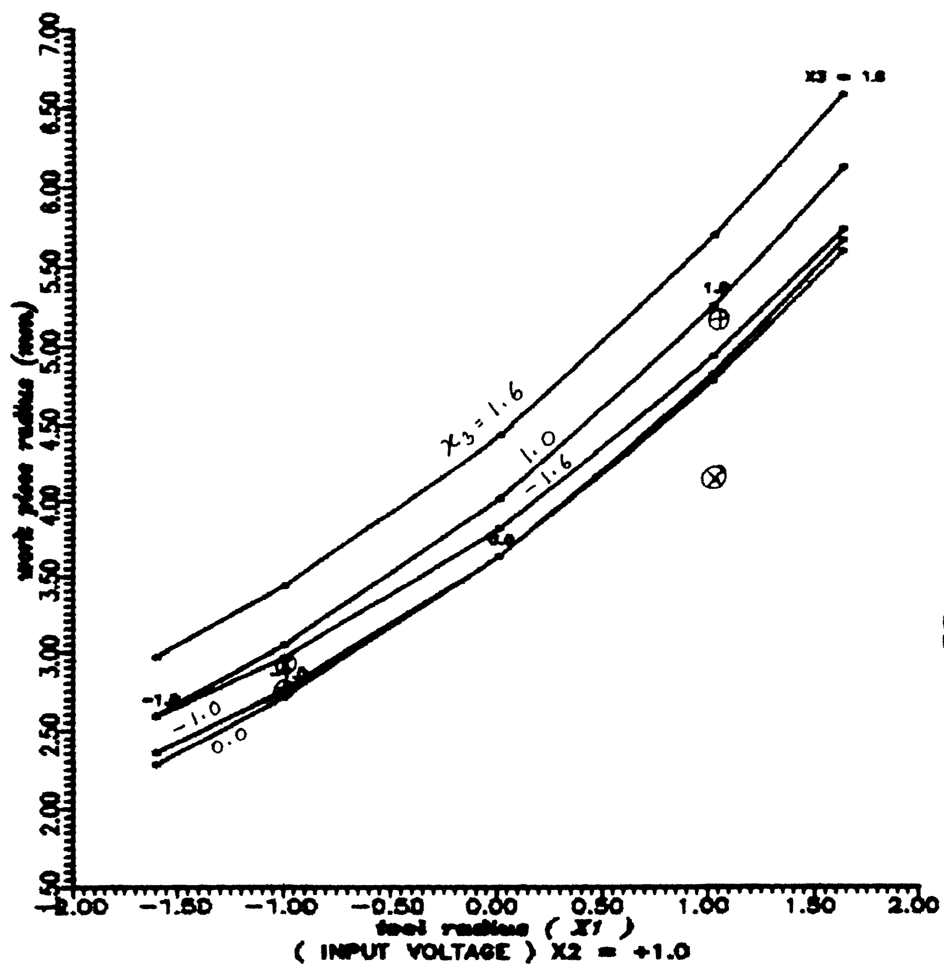


FIG. A 4

VARIATION OF WORKPIECE PROFILE RADIUS WITH TOOL PROFILE RADIUS

(CONVEX PROFILE TOOLS)

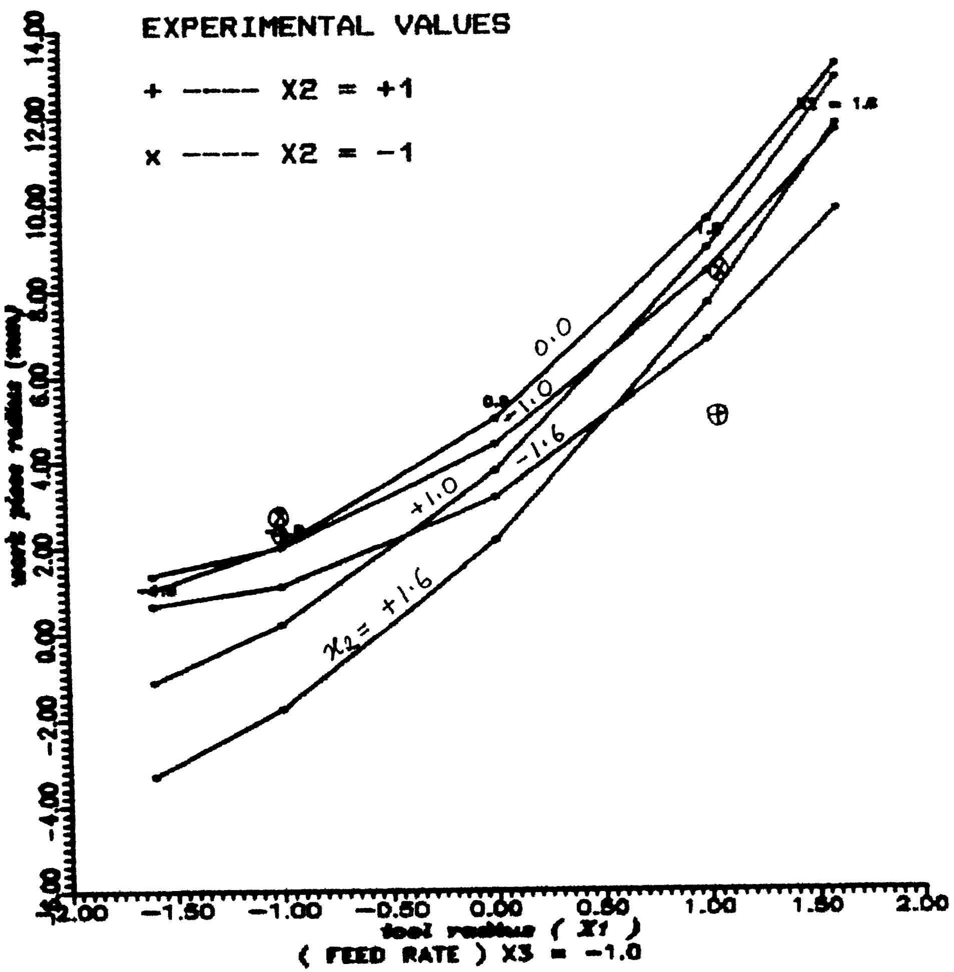


FIG. B 1

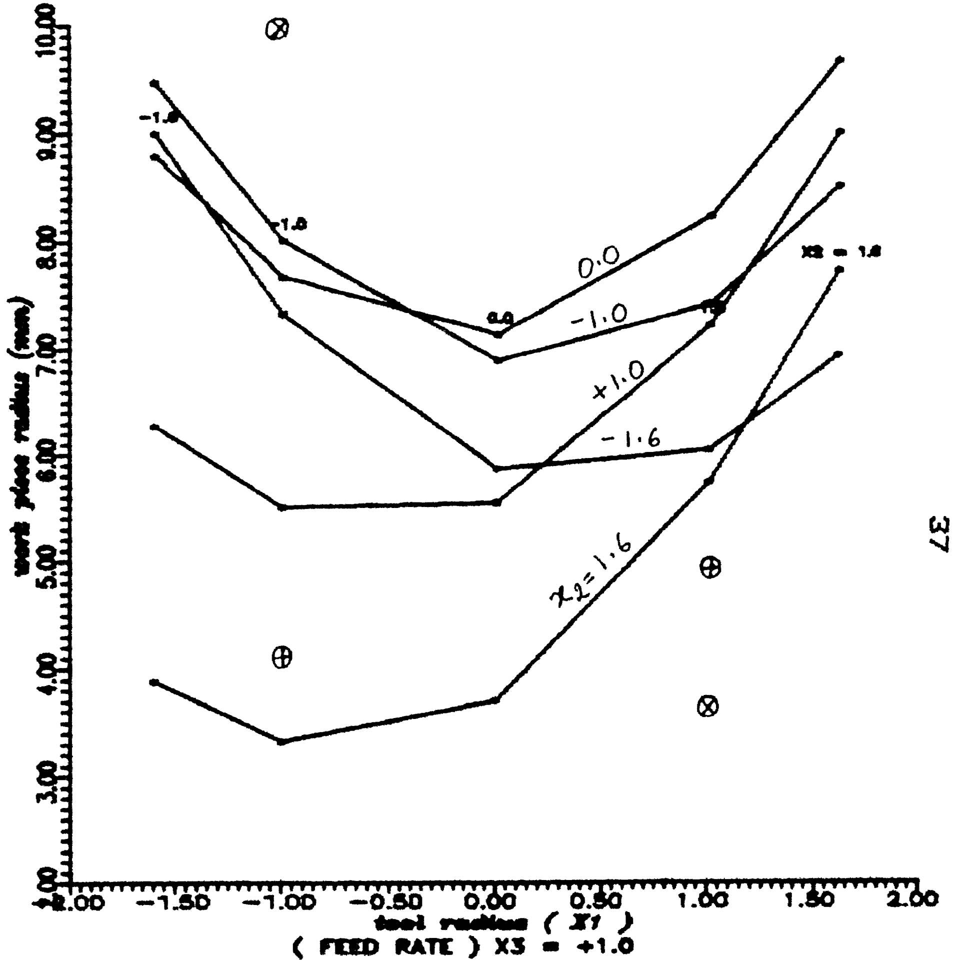


FIG. B 2

VARIATION OF WORKPIECE PROFILE RADIUS WITH TOOL PROFILE RADIUS

(CONCAVE PROFILE TOOLS)

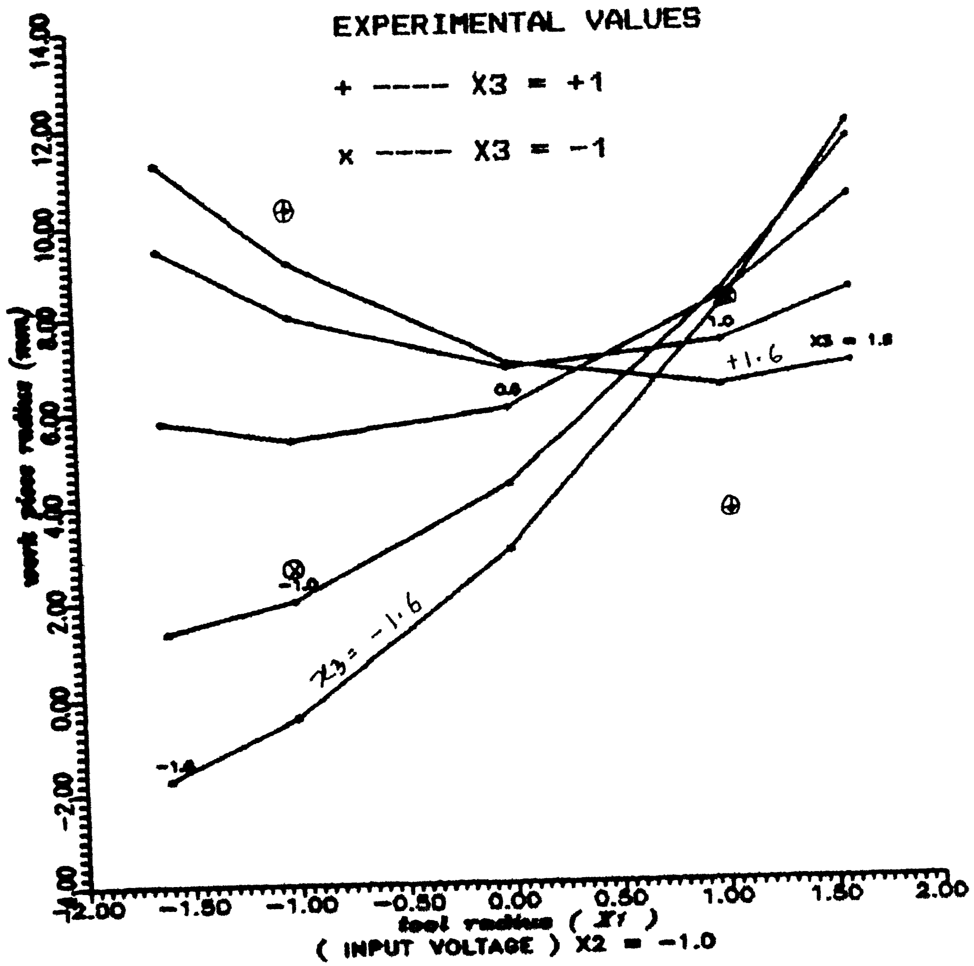


FIG. B 3

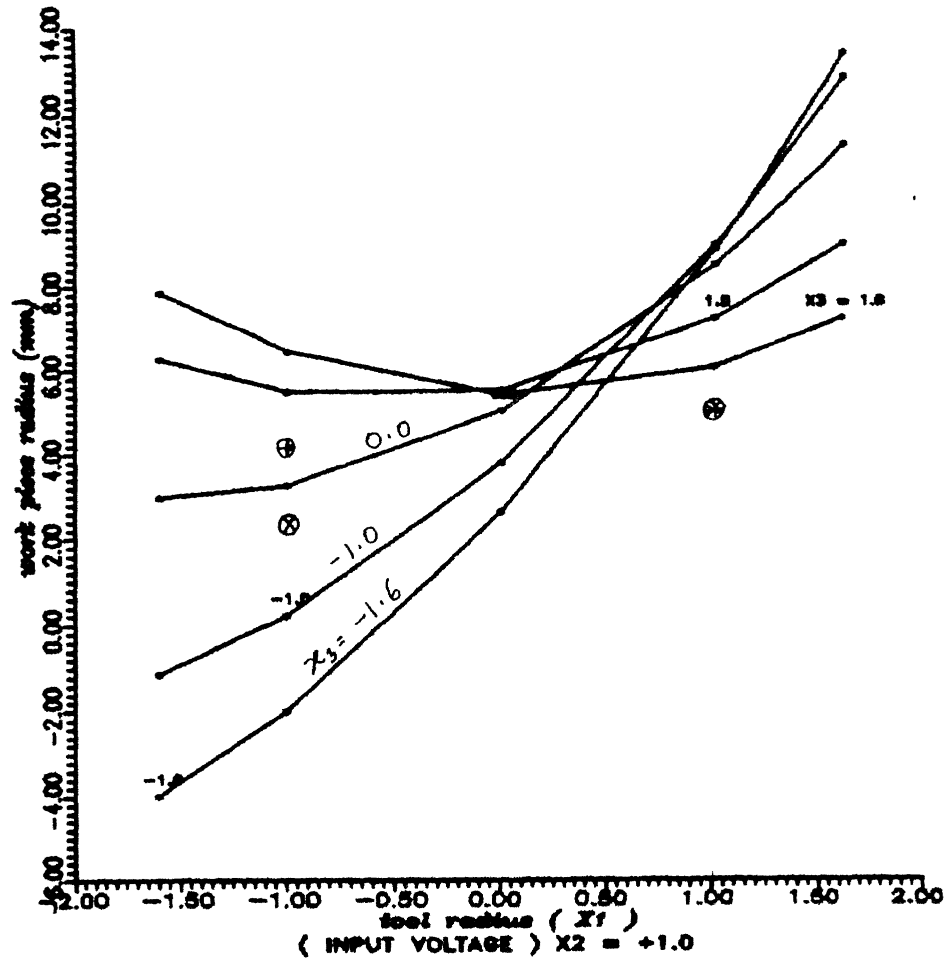


FIG. B 4

VARIATION OF WORKPIECE PROFILE RADIUS WITH TOOL PROFILE RADIUS

(CONCAVE PROFILE TOOLS)

o For *Constant Feed Rate* (x3)-

o The workpiece profile radius decreases initially with an increase in input voltage and then on increases continuously, for all chosen values of tool profile radii (x1). For any of the chosen values of input voltage the copied workpiece profile radius increases with the increase in tool profile radius as shown in [Figs. A5 and A6]. .

o For *Constant Tool Profile Radius* (x1)-

The value of workpiece profile radius decreases initially with an increase in input voltage and then on continuously increases for all values of feed rates (x3) chosen as shown in [Figs. A7 and A8].

b) CONCAVE TOOL PROFILES:

o For *Constant Feed Rate* (x3)-

o The copied workpiece profile radius initially increases with the increasing value of input voltages and then on decreases for all chosen values of tool profile radii (x1) as shown in [Figs. B5 and B6] .

This trend is exactly opposite to that exhibited by the curves obtained for experiments with convex tool profiles.

o For *Constant Tool Profile Radius* (x1)-

The workpiece profile radius increases initially with an increase in the input voltage and then decreases continuously for all chosen value of feed rate (x3) as shown in [Fig. B7 and B8].

This trend is also exactly opposite to that exhibited by the curves obtained with convex profile tools.

C. Effect of Feed Rate on Workpiece Profile Radius:

EXPERIMENTAL VALUES

+ ---- X1 = +1

x ---- X1 = -1

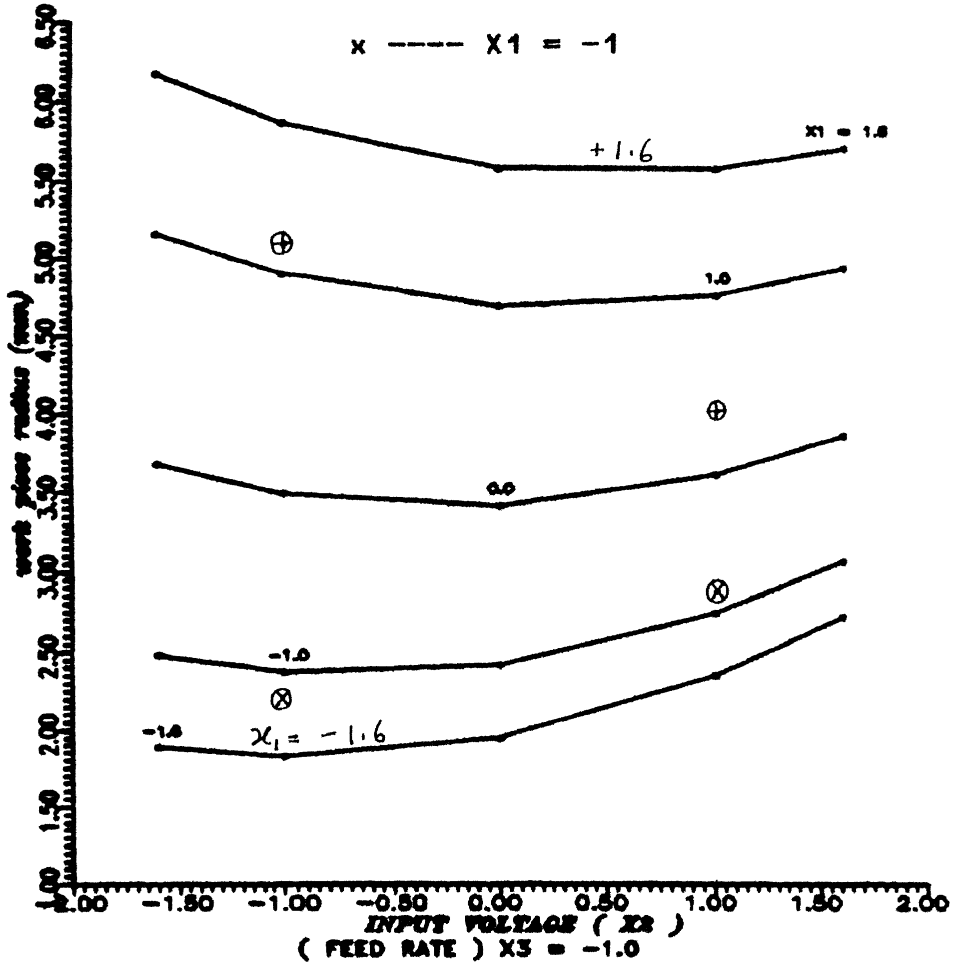


FIG. A 5

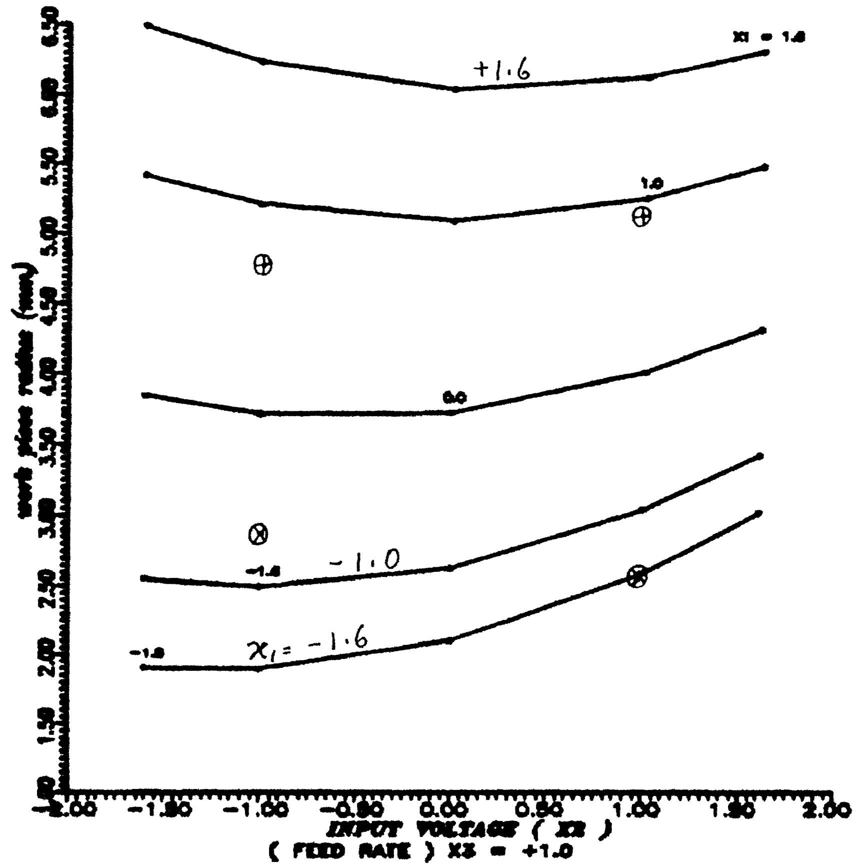
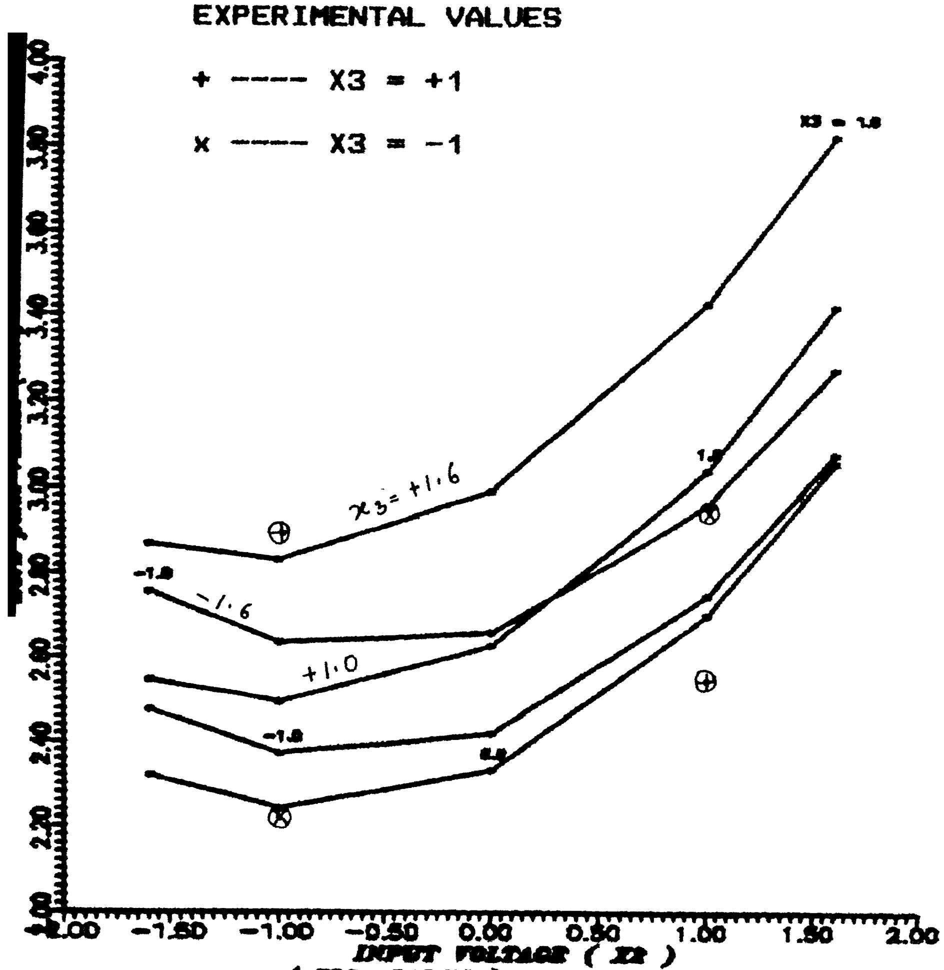


FIG. A 6

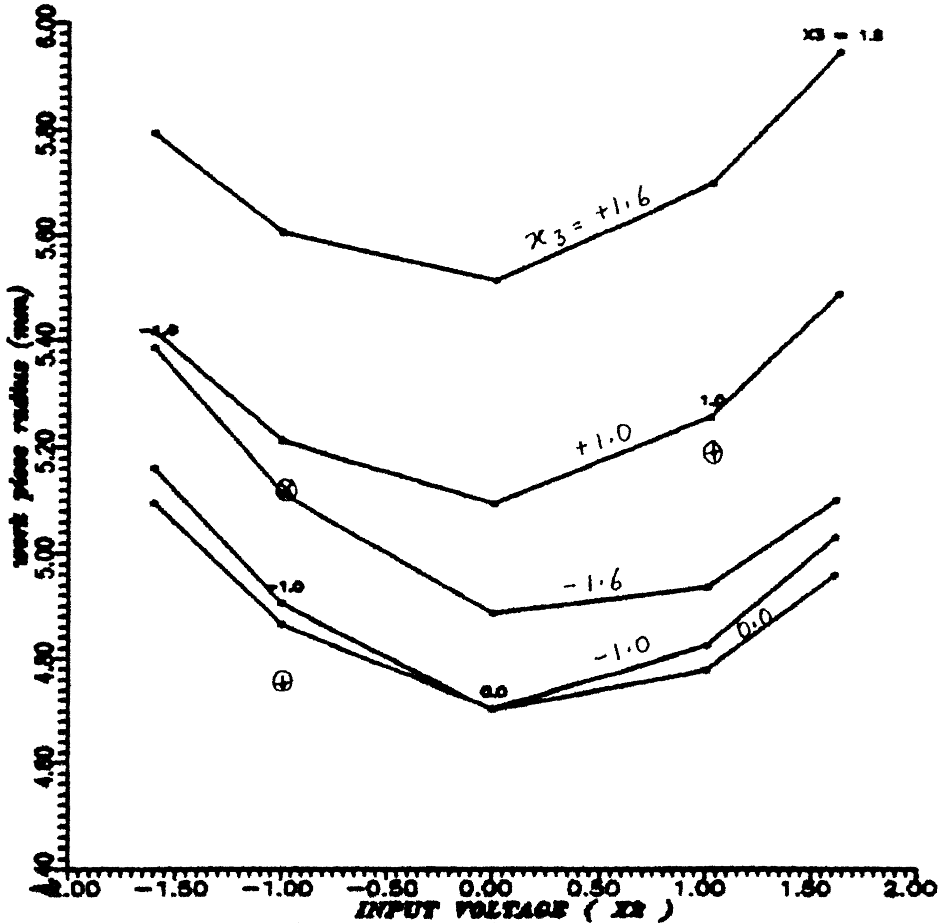
VARIATION OF WORKPIECE PROFILE RADIUS WITH INPUT VOLTAGE

(CONVEX PROFILE TOOLS)



(TOOL RADIUS) X1 = -1.0

FIG. A 7

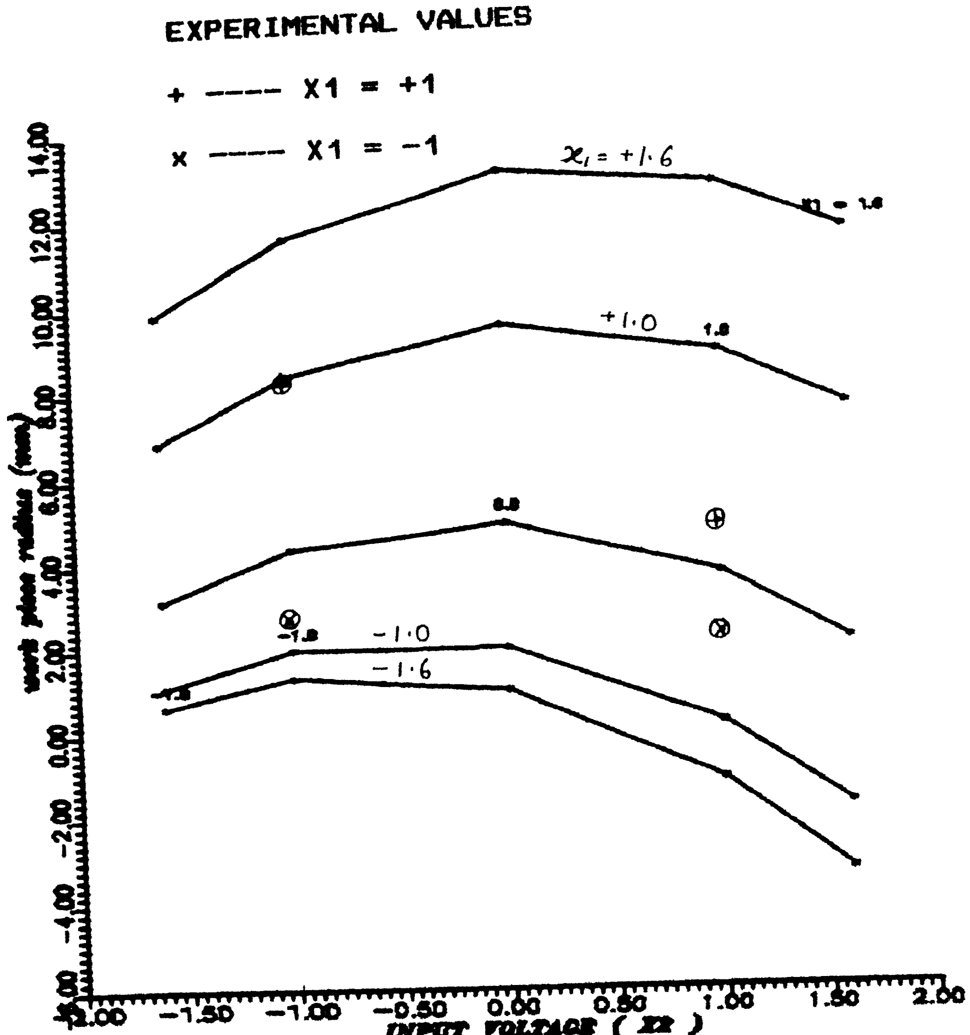


(TOOL RADIUS) X1 = +1.0

FIG. A 8

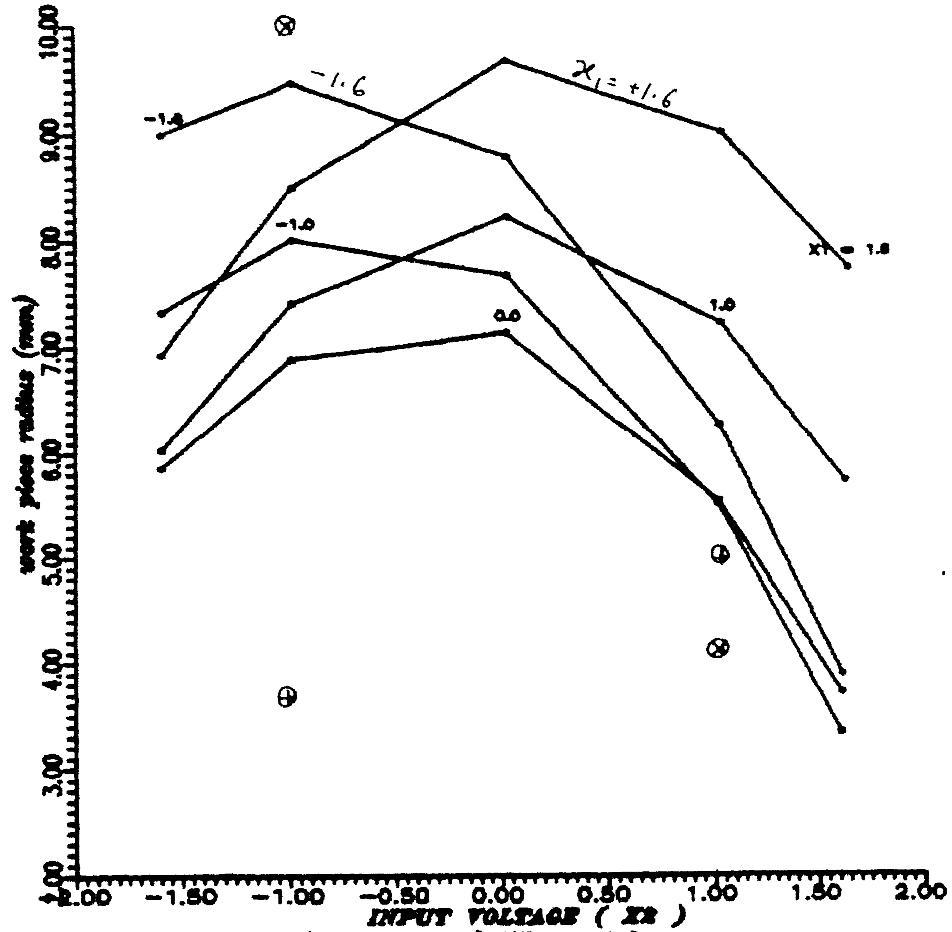
VARIATION OF WORKPIECE PROFILE RADIUS WITH INPUT VOLTAGE

(CONVEX PROFILE TOOLS)



(FEED RATE) X3 = -1.0

FIG. B 5



(FEED RATE) X3 = +1.0

FIG. B 6

VARIATION OF WORKPIECE PROFILE RADIUS WITH INPUT VOLTAGE

(CONCAVE PROFILE TOOLS)

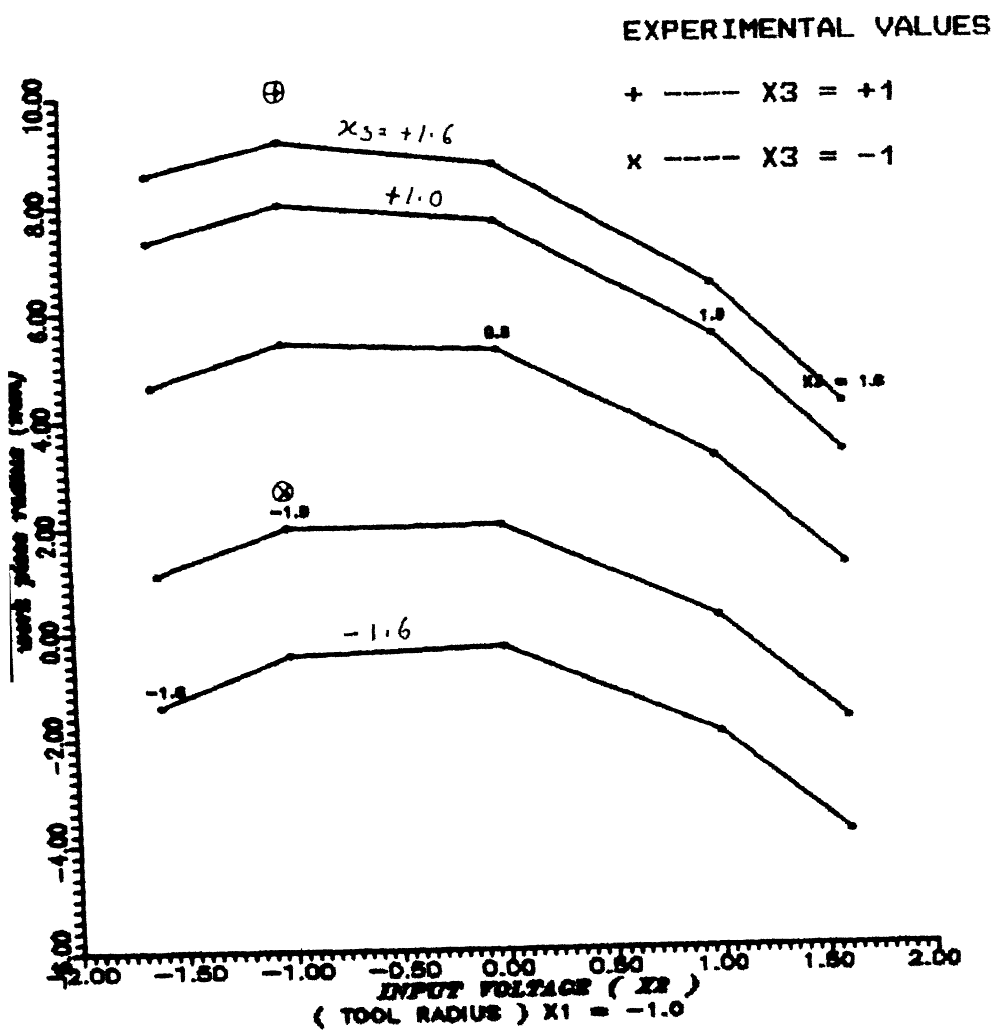


FIG. B 7

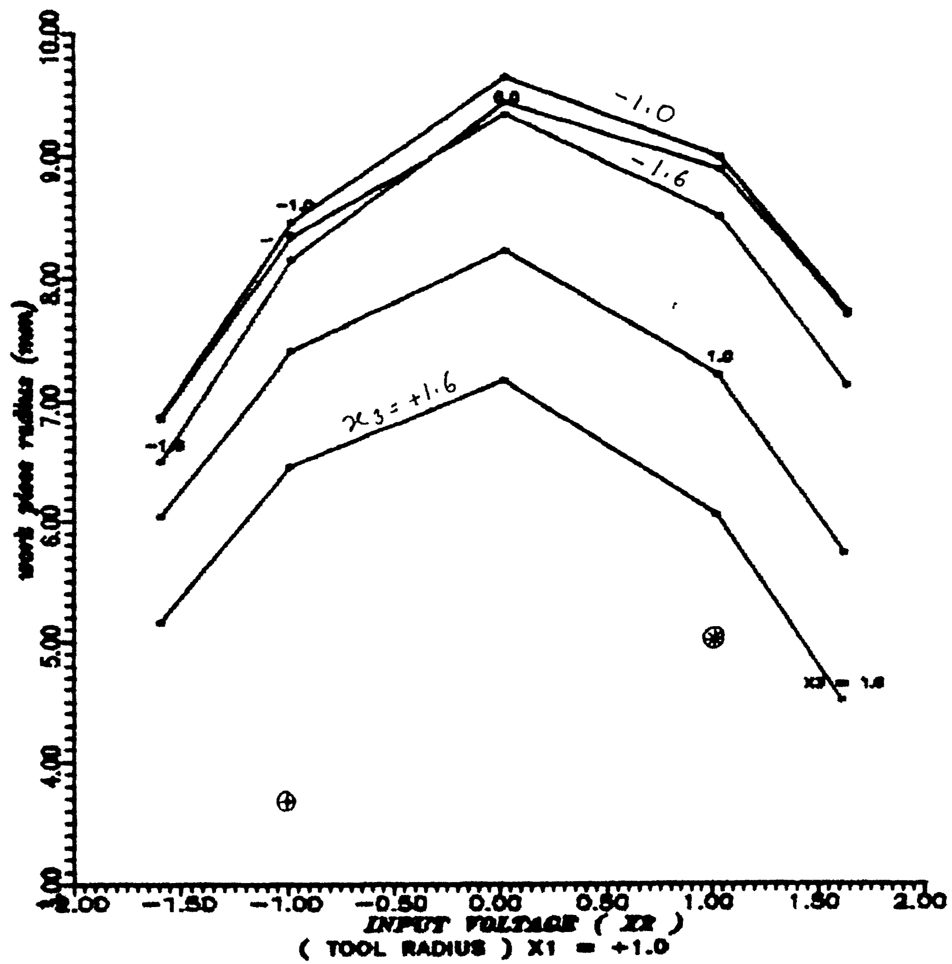


FIG. B 8

VARIATION OF WORKPIECE PROFILE RADIUS WITH INPUT VOLTAGE

(CONCAVE PROFILE TOOLS)

a) CONVEX TOOL PROFILES

The workpiece profile radius decreases with increase in feed rate upto a certain value and then on increases for all chosen values of input voltages and tool radii while tool radii and input voltages are kept constant in the corresponding cases as shown in [Figs. A9 ... A12]

b) CONCAVE TOOL PROFILES:

o For *Constant Input Voltage* (x2)-

The workpiece profile radius increases with increasing value of feed rate upto a certain value of the tool profile radius while beyond, it increases first and then decreases upto a certain value of tool profile radius and for even higher values of tool profile radius, it continuously decreases as shown in [Figs. B9 and B10] .

o For *Constant Tool Profile Radius* (x1)-

No common trend is available for the variation of workpiece profile radius with feed rate (x3) since, for values of tool profile radius, x1 = -1.0 (coded value) the workpiece profile radius continuously increases with an increase in the feed rate for all chosen values of input voltages, while for x1 = 1.0, the workpiece profile radius increases first and then decreases continuously for almost all the values of input voltages chosen except in one case, wherein it decreases continuously as shown in [Figs. B11 and B12].

This trend is also completely different from that exhibited by curves obtained by use of convex profile tools.

3.4 Discussion:

o The experimental points plotted in the graphs show

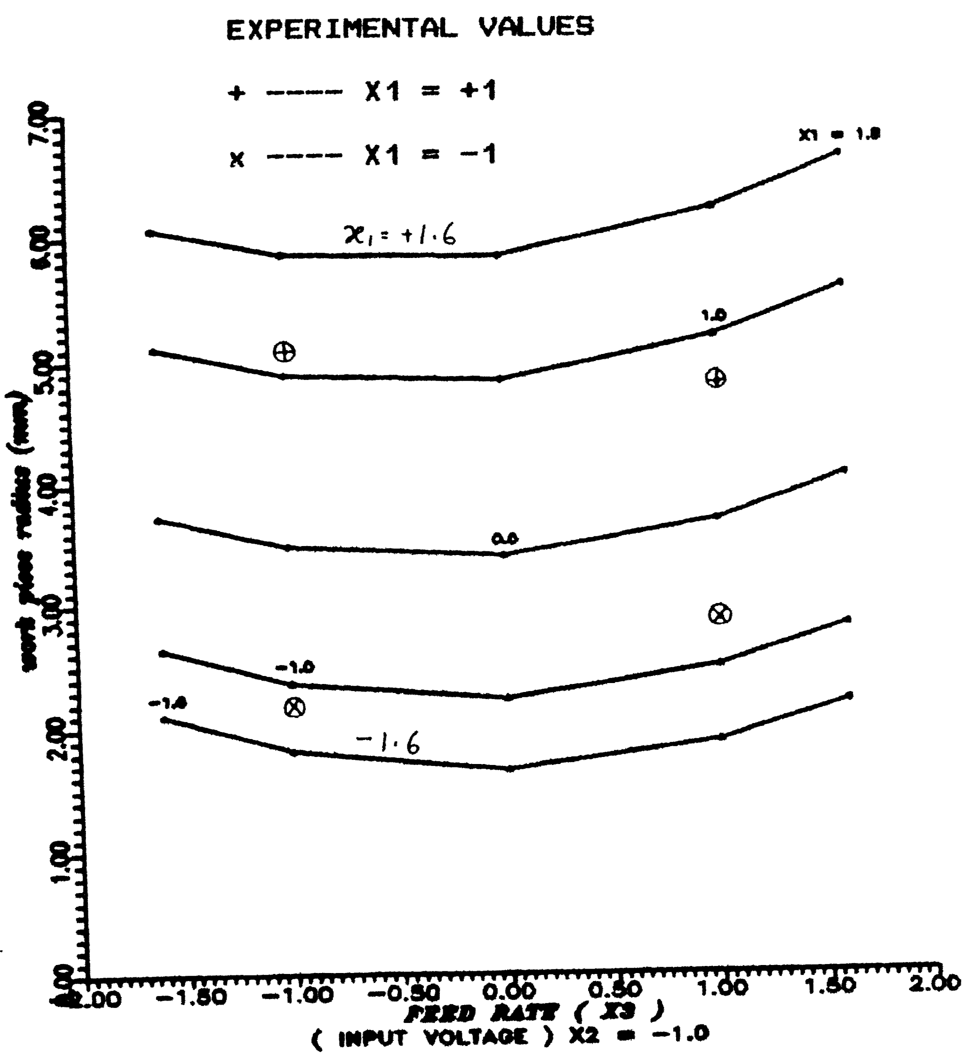


FIG. A 9

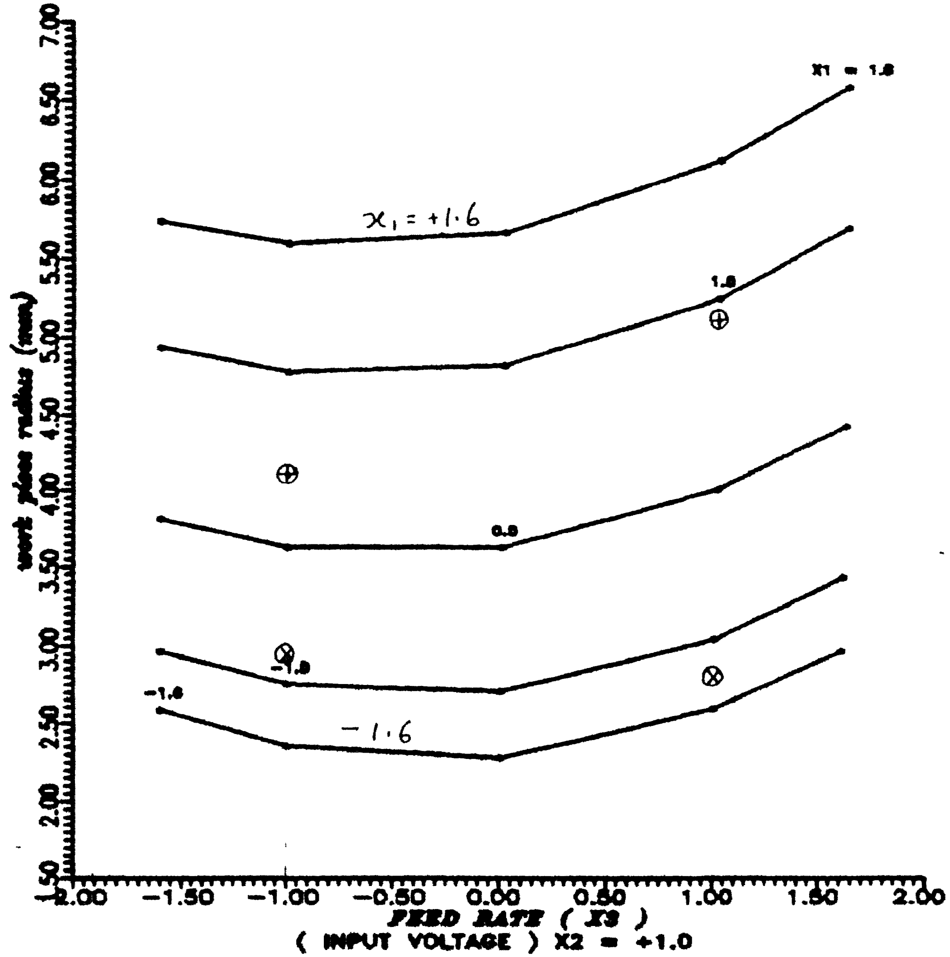
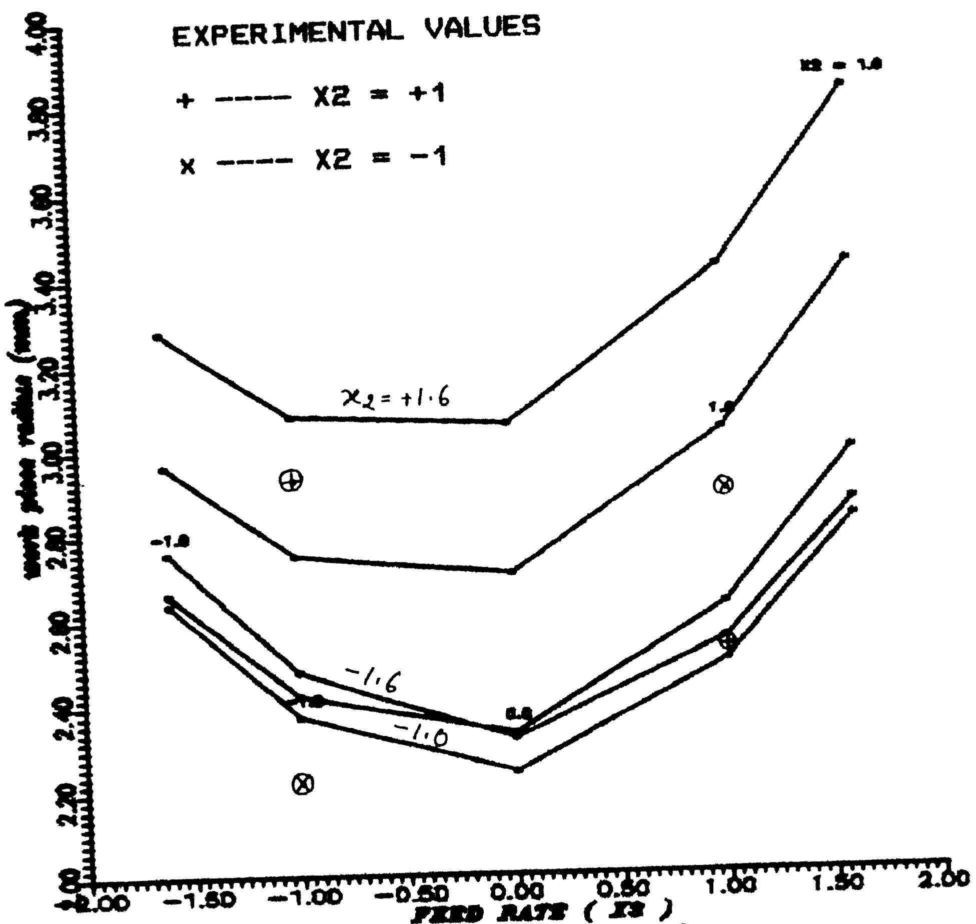


FIG. A 10

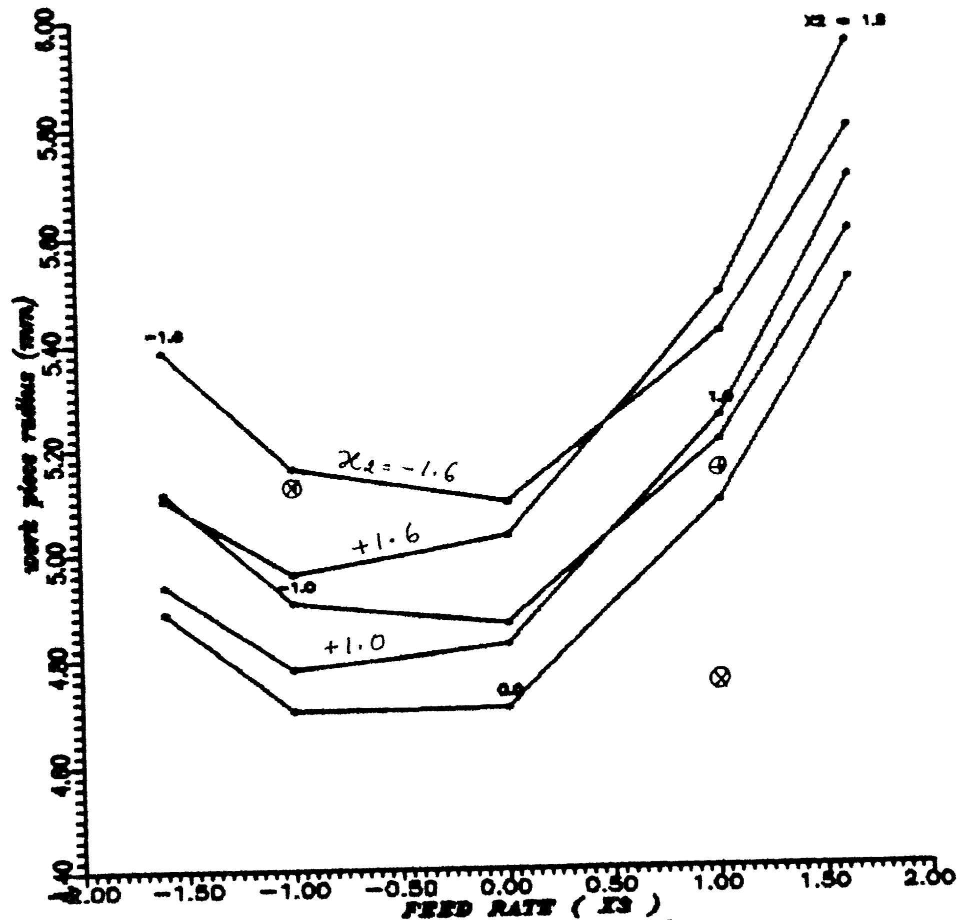
VARIATION OF WORKPIECE PROFILE RADIUS WITH FEED RATE

(CONVEX PROFILE TOOLS)



(TOOL RADIUS) X1 = -1.0

FIG. A 11



(TOOL RADIUS) X1 = +1.0

FIG. A 12

VARIATION OF WORKPIECE PROFILE RADIUS WITH FEED RATE

(CONVEX PROFILE TOOLS)

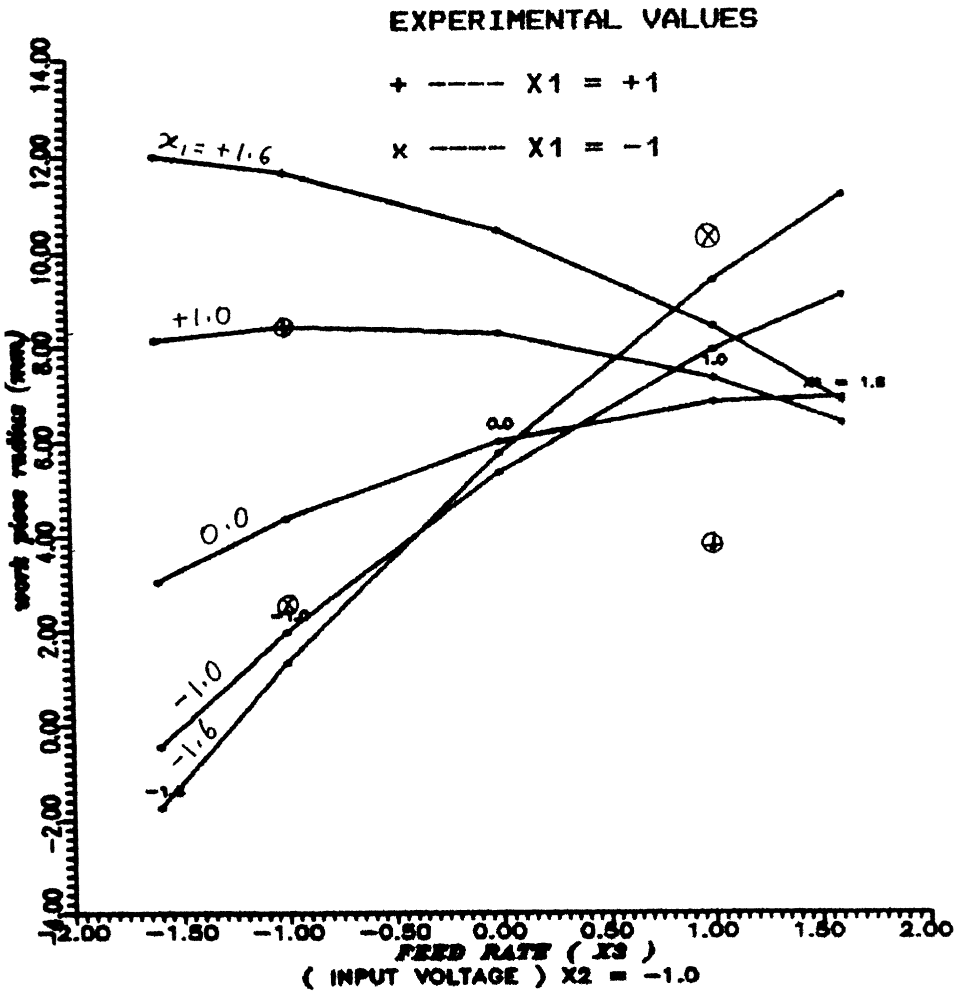


FIG. B 9

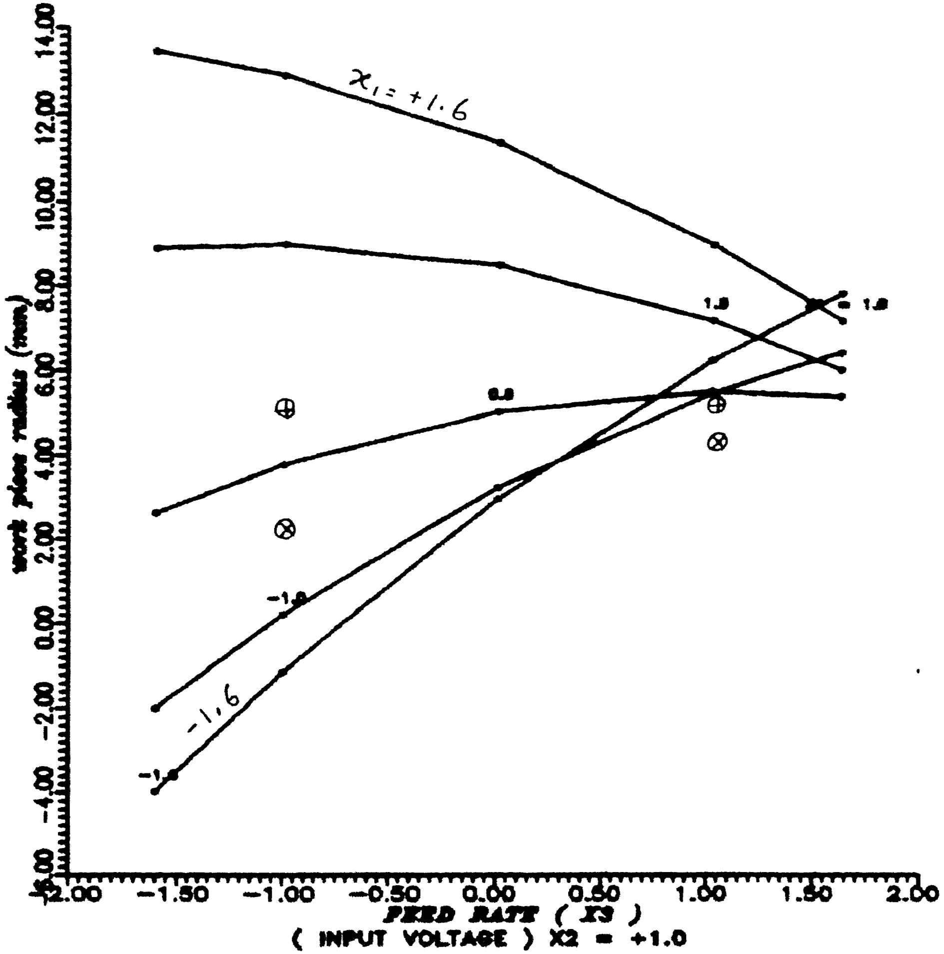
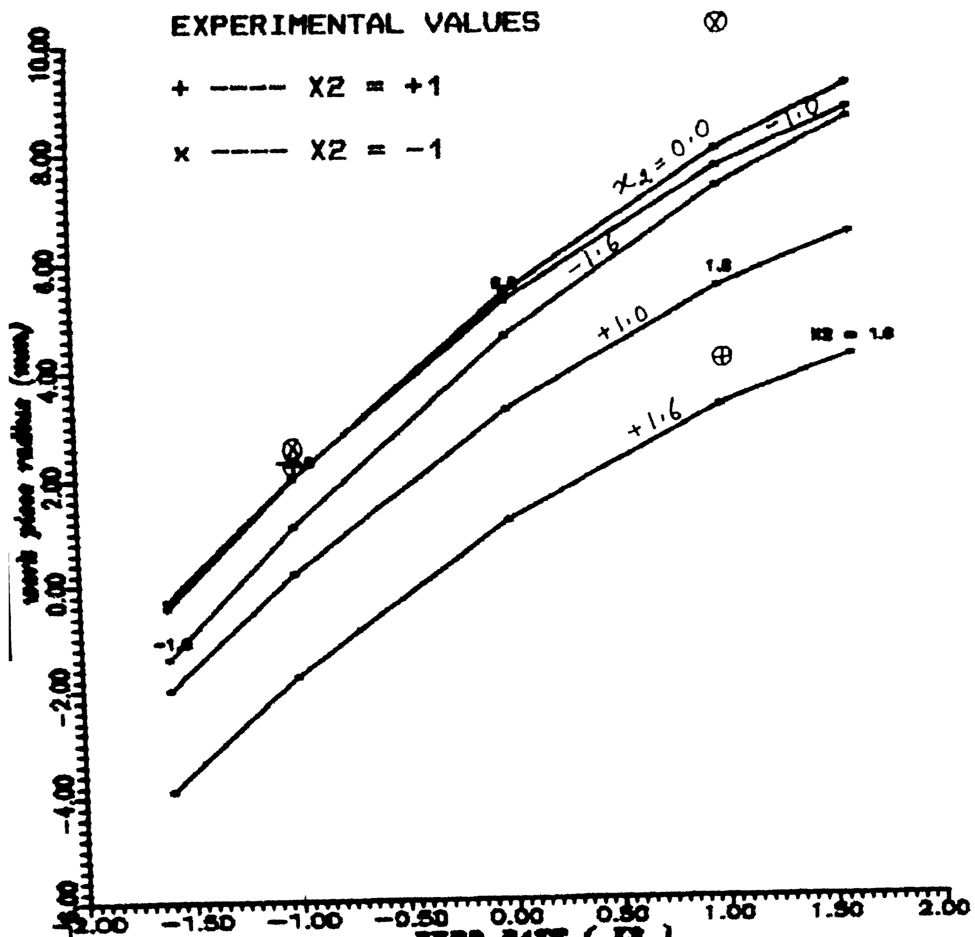


FIG. B 10

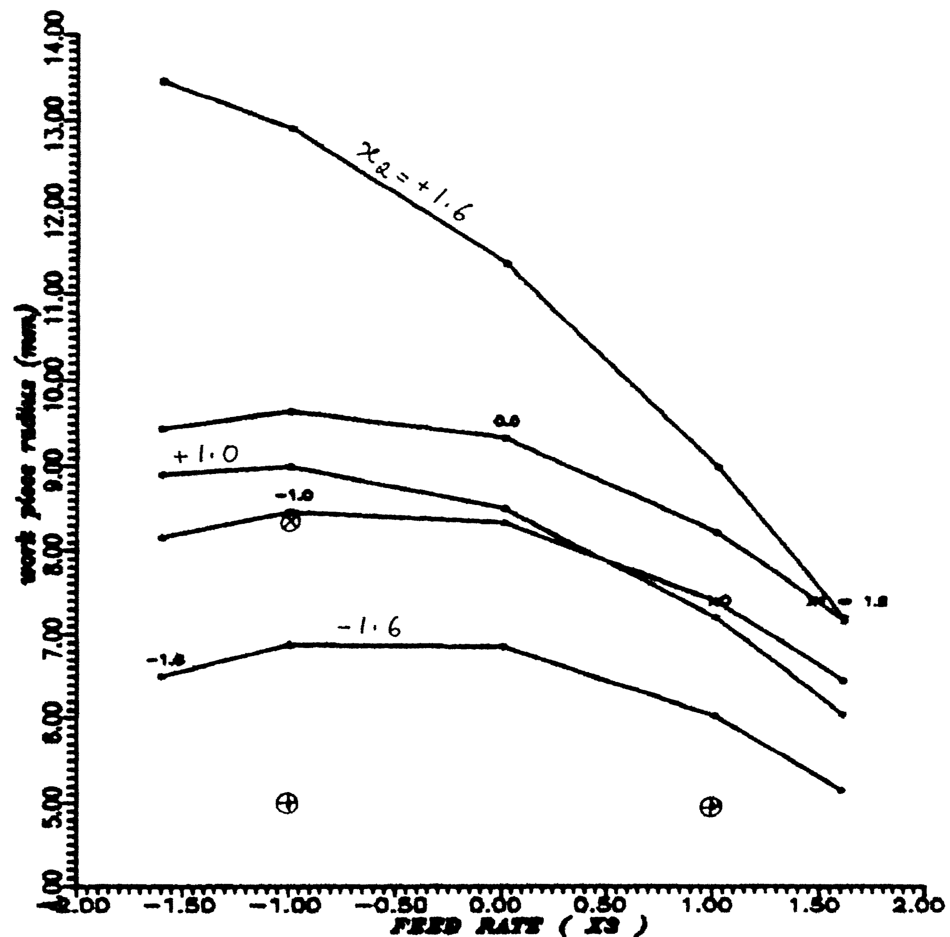
VARIATION OF WORKPIECE PROFILE RADIUS WITH FEED RATE

(CONCAVE PROFILE TOOLS)



(TOOL RADIUS) X1 = -1.0

FIG. B 11



(TOOL RADIUS) X1 = +1.0

FIG. B 12

VARIATION OF WORKPIECE PROFILE RADIUS WITH FEED RATE

(CONCAVE PROFILE TOOLS)

satisfactory agreement between the actual values obtained in the experimental values and those represented by the postulated model.

o The scatter of these points are probably due to -

a) instability of the process mainly attributed to the use of stepper motor to control the feed, as it enables the feed in intermittent steps, though at equal and very small intervals of time as shown in Tables 3.1 .. 3.4 and Fig. C1..C6 and D1..D6 giving the process current history during the experiments.

b) Errors in measurement that could have possibly crept in due to -

i) The use of replica technique to measure the radius of the copied profile on the workpieces, since some shrinkage of the replica material cannot be avoided.

ii) The streations that were left behind by the process on the machined surface of a few of the workpieces (streations visible in photographs of one of the specimens, Fig. 2.5).

c) The small difference between the values of the levels of the parameters that could be achieved for use in the experiments and those that should have been ideally used as per design of experiments as shown in Tables 2.2, A and B (Chapter 2).

TABLE 3.1

Time secs.)	Experiment Code (for Concave tool profile) D2	B1	C2	C3	C4	B3	D4
0	10	20	20	20	20	20	10
30	20	30	20	30	20	20	20
60	20	30	20	50	30	40	20
90	30	40	20	70	50	50	20
120	40	50	20	80	70	70	20
150	50	50	20	90	70	70	20
180	60	50	30	100	80	70	30
210	50	50	40	110	70	60	50
240	60	50	50	100	80	40	60
270	60	50	70	80	80	50	50
300	60	50	80	100	100	70	60
330	60	60	60	120	100	70	70
360	60	60	80	110	80	60	80
390	60	50	100	120	100	40	70
420	50	60	90	100	100	90	80
450	60	70	90	130	130	100	60
480	60	70	100	140	100	100	80
510	50	80	60	120	140	120	80
540	60	70	90	130	150	100	60
570	60	90	60	150	180	130	90
600	70	80	90	160	100	160	90
630	80	100	100	140	200	150	90
690	70	110	80	160	180	100	90
720	80	100	100	170	180	150	70
750	60	110	80	120	180	150	100
780	80	130	60	140	170	150	90
810	60	90	100	150	170	150	110
830	80	140	80	160	170	140	110
860	80	130	100	150	180	150	100
890	70	110	90	140	170	150	110
920	80	130	100	170	170	100	90
950	100	140	90	150	170	150	100
980	70	140	100	170	190	90	90

1010	120	150	90	170	180	150	100
1040	130	140	100	140	180	150	100
1070	140	100	110	160	190	150	110
1100	150	140	100	170	190	90	100
1130	150	90	100	140	0	150	90
1160	140	150	90	160	0	100	110
1190	150	150	100	170	0	150	110
1220	130	90	100	160	0	90	120
1250	140	110	100	170	0	150	90
1280	130	130	80	140	0	90	100
1310	90	150	110	150	0	150	110
1340	110	150	100	170	0	150	100
1370	130	0	100	150	0	150	0
1400	130	0	100	0	0	0	0
1430	100	0	100	0	0	0	0
1470	130	0	0	0	0	0	0
1500	130	0	0	0	0	0	0

TABLE 3.2

Time secs.)	Experiment Code (for Concave tool profile) E9	E2	E4	E5	E6	E7	E8
0	20	30	20	20	20	30	30
30	30	40	30	40	20	40	40
60	40	30	90	80	20	60	70
90	70	70	90	80	30	80	80
120	90	100	90	90	60	80	80
150	90	100	130	90	80	90	90
180	70	90	140	90	80	100	100
210	90	90	120	90	80	100	100
240	90	90	150	100	90	90	90
270		50	160	140	90	100	100
300	100	100	170	140	90	130	100
330	100	100	180	150	100	130	110
360	120	90	110	100	140	130	140
390	130	100	180	150	150	130	140
420	150	100	180	130	120	140	130
450	150	130	170	140	140	150	140
480	130	140	180	130	140	120	140
510	130	140	110	140	140	120	140
540	140	160	190	130	150	140	140
570	150	160	180	130	110	120	140
600	100	80	180	100	130	150	140
630	150	100	180	110	120	140	110
690	140	140	180	140	150	140	140
720	140	140	190	160	150	100	140
750	150	140	140	160	140	150	150
780	120	140	180	150	150	150	100
810	160	140	0	160	150	140	150
830	120	150	0	160	150	140	150
860	150	100	0	100	0	140	140
890	150	160	0	150	0	140	150
920	150	160	0	150	0	150	150
950	150	0	0	0	0	0	0
980	160	0	0	0	0	0	0

TABLE 3.3

Time secs.)	Experiment Code (for Convex tool profile) C3	B1	C2	C3	C4	D3	D4
0	20	20	20	20	20	30	30
30	20	20	20	20	30	40	40
60	30	30	30	30	50	60	60
90	50	50	50	50	60	80	70
120	80	60	60	80	70	100	70
150	80	80	70	100	80	130	80
180	80	80	90	130	80	130	80
210	100	80	90	130	80	130	80
240	100	90	90	130	90	140	80
270	100	100	90	140	90	150	90
300	110	120	100	150	90	150	90
330	120	110	100	150	90	140	90
360	120	120	100	140	90	140	90
390	110	110	100	150	90	150	90
420	110	120	100	150	100	160	100
450	110	130	100	150	90	150	100
480	110	120	100	150	100	150	100
510	120	120	100	150	110	150	100
540	120	130	100	150	120	150	100
570	120	140	100	140	100	150	100
600	120	130	100	150	100	150	100
630	120	120	110	150	100	150	100
690	120	140	110	150	100	150	100
720	120	130	110	150	100	150	100
750	120	140	100	150	100	150	100
780	120	140	110	150	100	150	100
810	120	140	110	150	100	150	100
830	130	140	110	150	100	0	100
860	120	140	110	150	100	0	100
890	130	140	110	0	100	0	100
920	120	140	110	0	100	0	100
950	120	0	100	0	100	0	100
980	120	0	110	0	100	0	100

TABLE 3.4

Time secs.)	Experiment Code (for CONVEX tool profile) E7	E2	E4	E5	E6	E8	E9
0	20	20	20	20	20	20	20
30	30	30	30	30	30	30	30
60	40	50	50	30	40	40	40
90	70	60	70	40	70	70	70
120	70	80	90	70	90	80	70
150	90	90	110	90	100	90	90
180	100	100	130	100	100	100	100
210	100	110	140	100	110	100	110
240	120	100	140	100	130	100	100
270	120	110	140	110	130	110	120
300	120	120	150	130	140	110	110
330	130	130	160	140	130	130	130
360	130	130	160	140	130	140	130
390	130	130	160	130	140	140	120
420	130	130	150	130	140	140	120
450	130	130	150	130	140	130	130
480	130	130	170	140	140	140	130
510	140	140	170	140	130	140	140
540	140	140	150	140	140	140	140
570	140	130	160	130	130	130	140
600	130	130	170	130	140	130	130
630	130	130	170	130	130	130	130
690	140	140	170	140	140	140	130
720	140	140	170	140	130	140	130
750	140	130	160	130	140	130	130
780	140	140	160	140	140	140	140
810	140	140	160	140	140	130	130
830	130	140	160	130	140	140	130
860	130	130	160	150	140	140	130
890	110	140	160	140	140	140	130
920	140	140	150	140	140	130	130
950	130	130	160	140	140	130	130
980	140	140	170	140	140	130	140

1020	140	130	160	140	140	130	130
1050	140	130	0	140	0	140	130
1080	140	0	0	140	0	0	140
1110	140	0	0	0	0	0	0

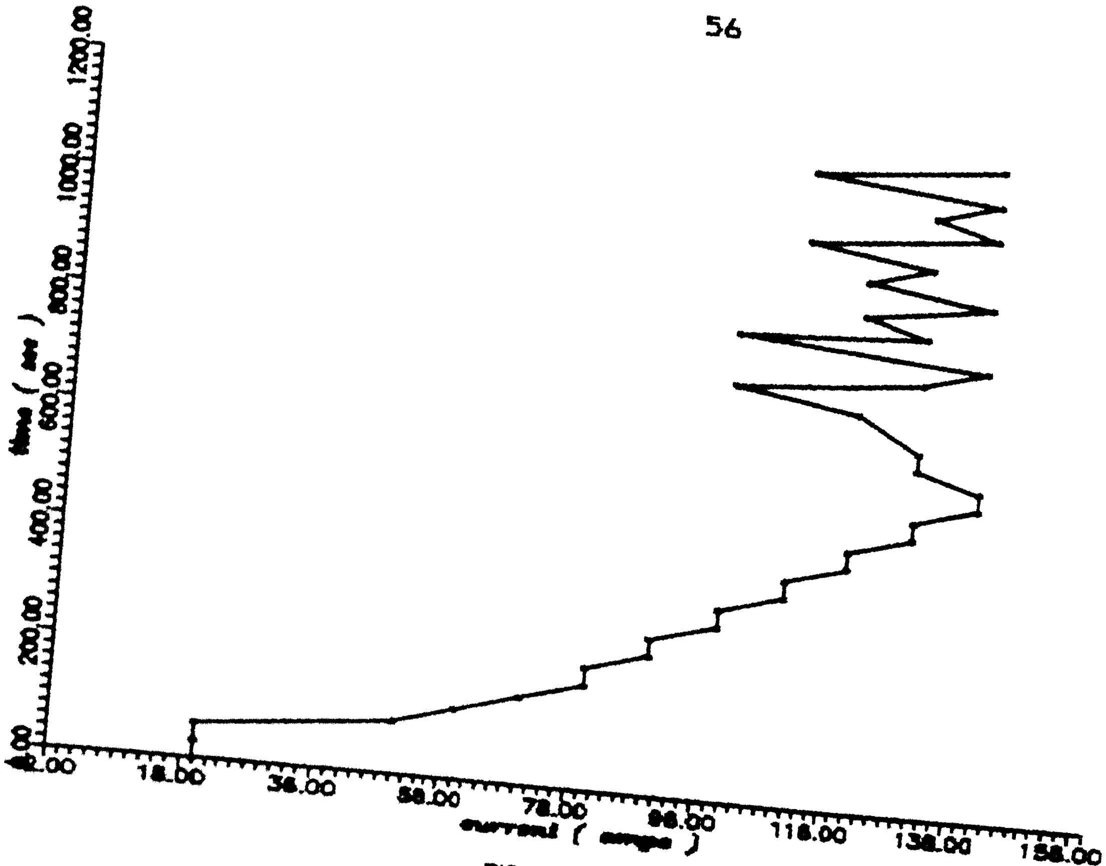


FIG. C 1 EXPT. CODE - A1

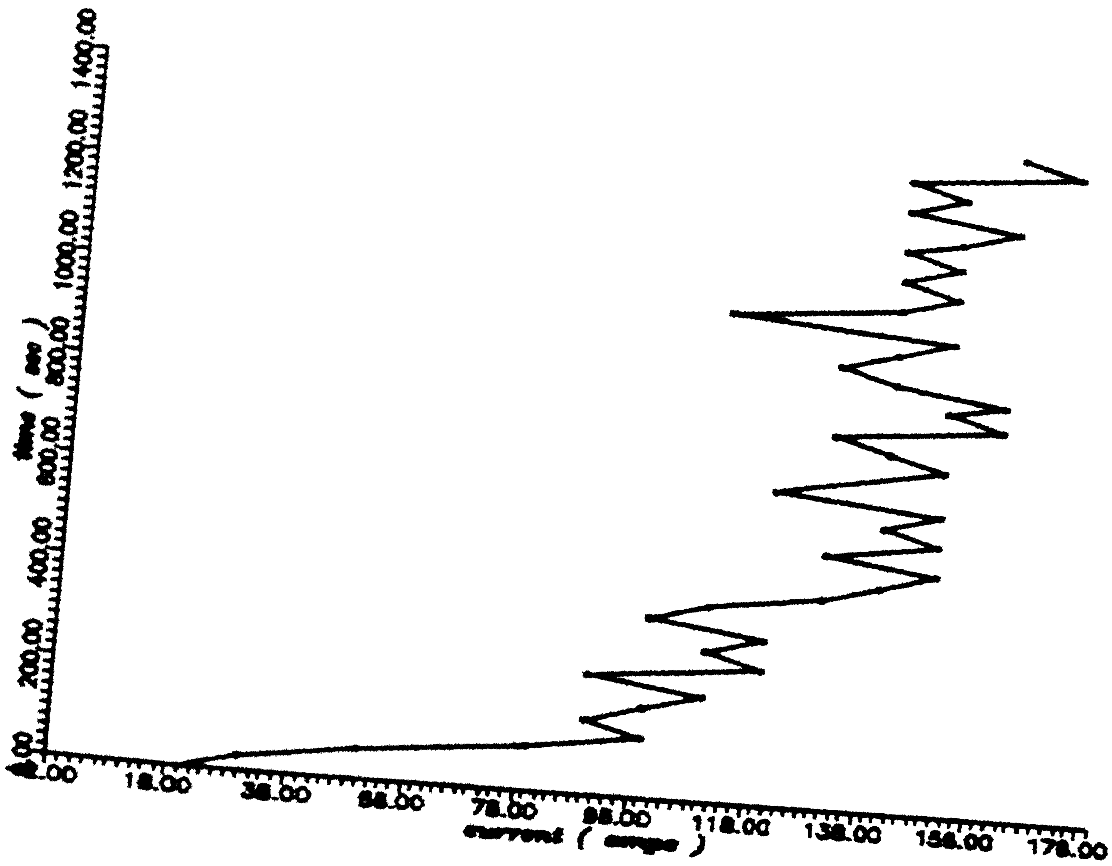


FIG. C 2 EXPT. CODE - C1

CURRENT HISTORY (CONCAVE PROFILE TOOLS)

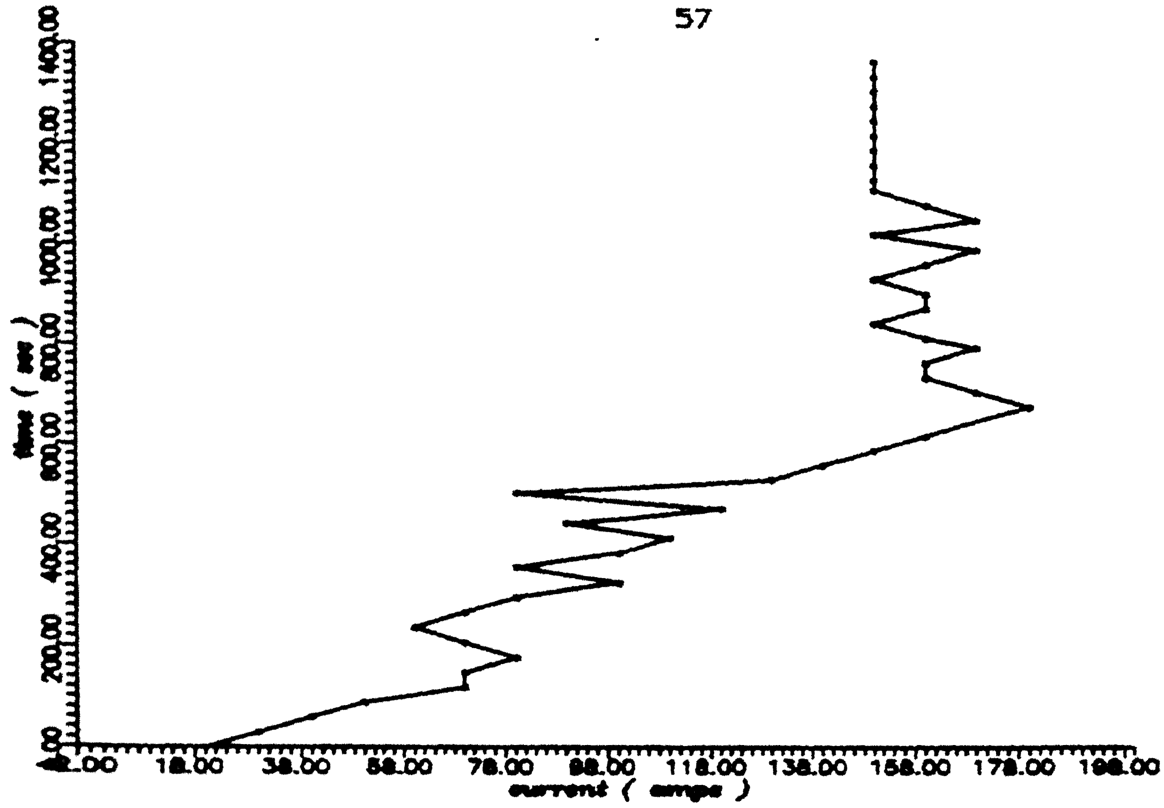


FIG. C 3 EXPT. CODE - B1

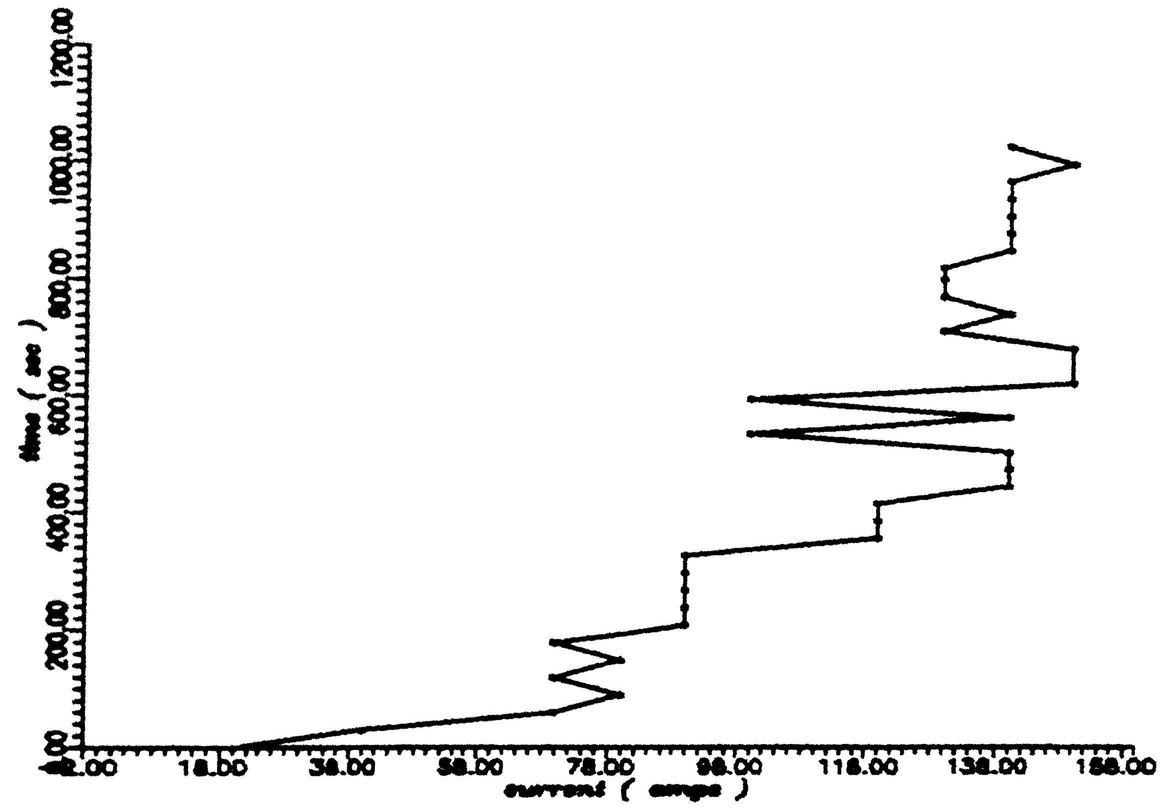


FIG. C 4 EXPT. CODE - E1

CURRENT HISTORY (CONCAVE PROFILE TOOLS)

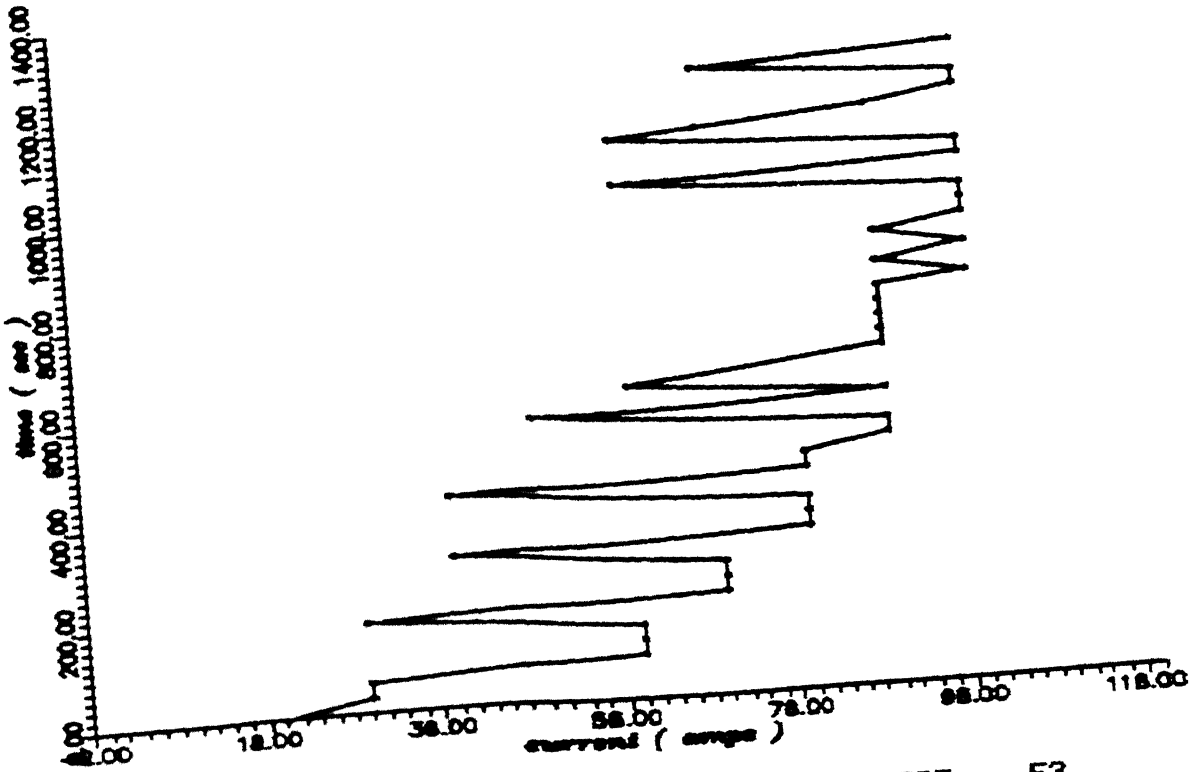


FIG. C 5 EXPT. CODE - E3

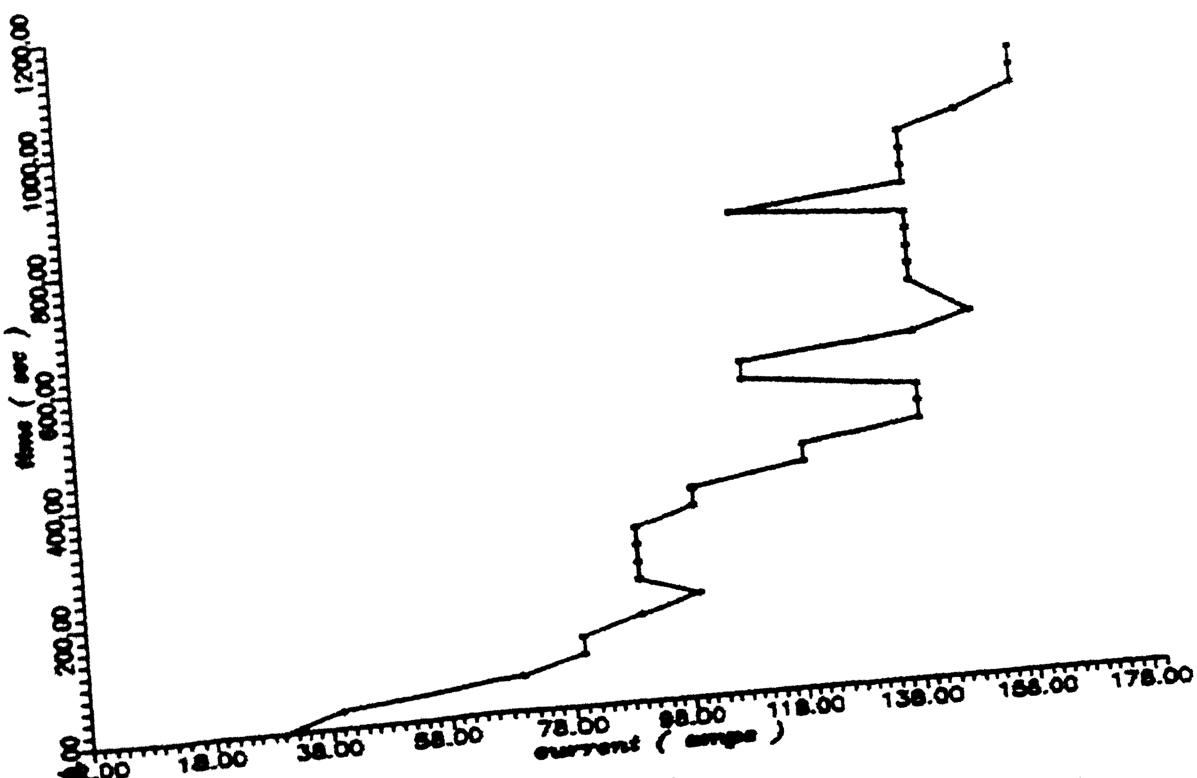


FIG. C 6 EXPT. CODE - E10

CURRENT HISTORY (CONCAVE PROFILE TOOLS)

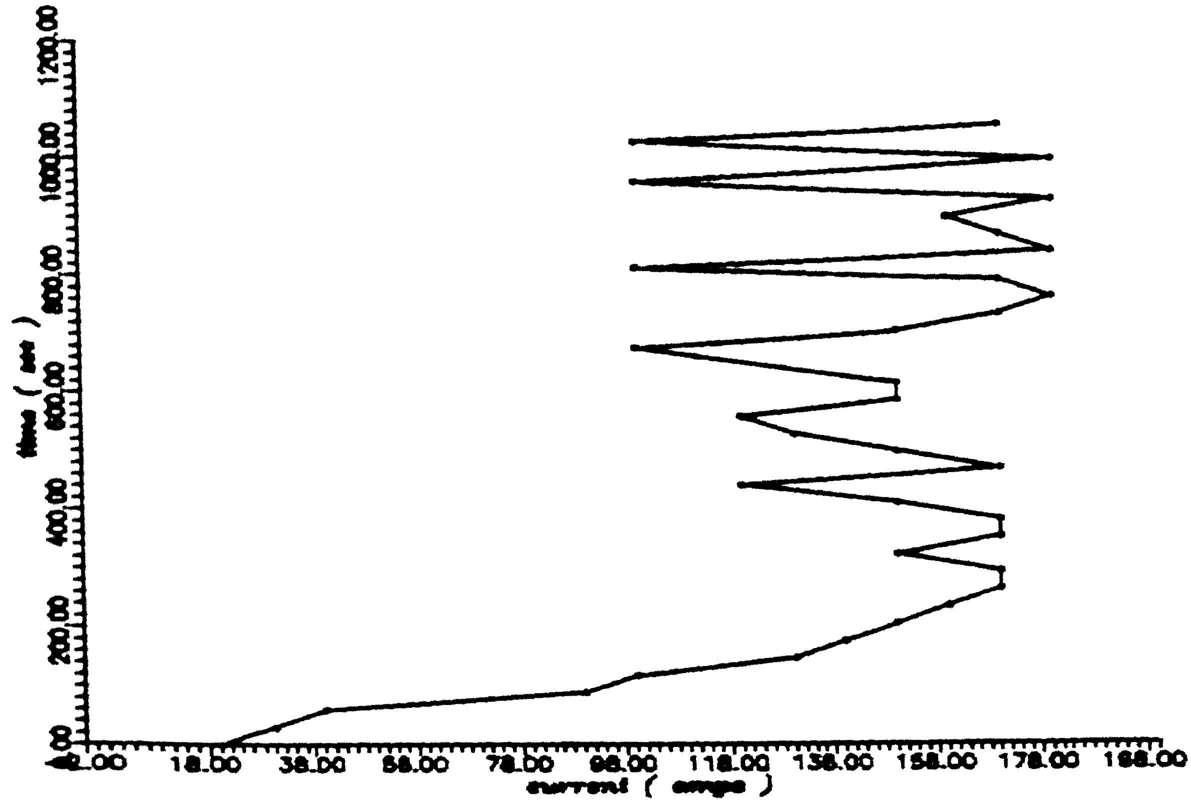


FIG. D 1 EXPT. CODE - A1

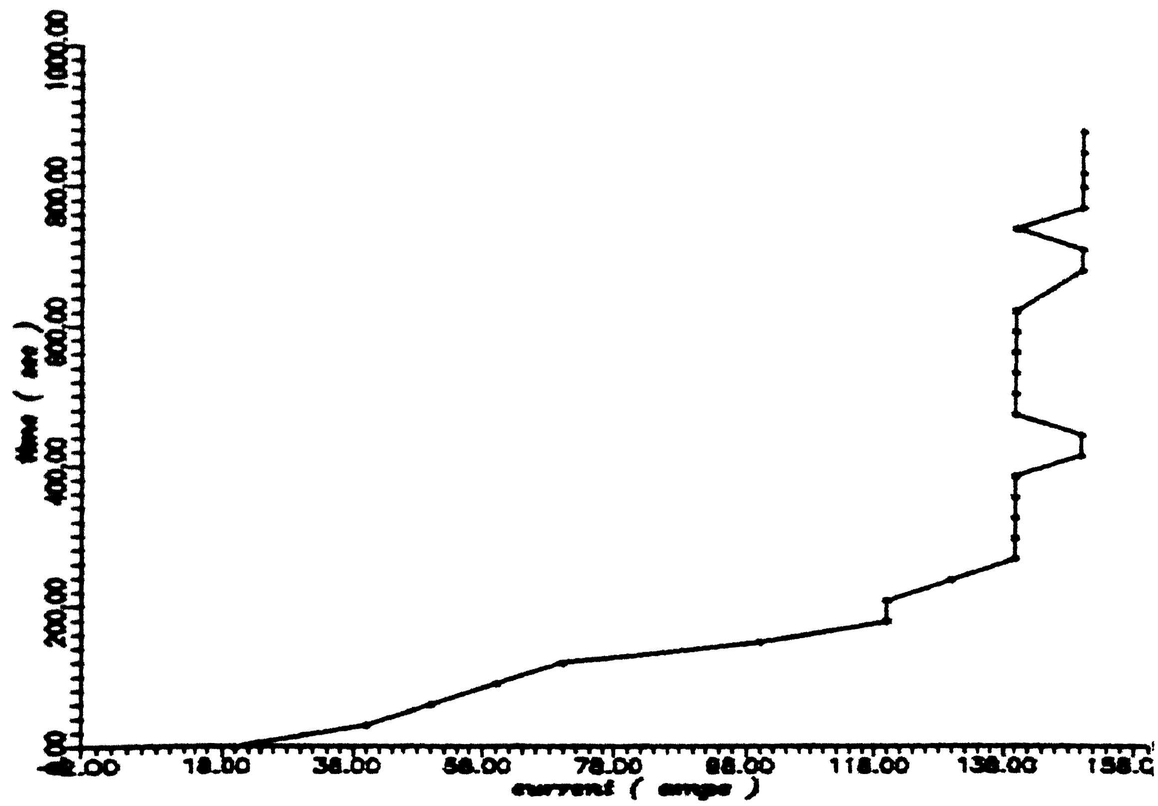


FIG. D 2 EXPT. CODE - B1

CURRENT HISTORY (CONVEX PROFILE TOOLS)

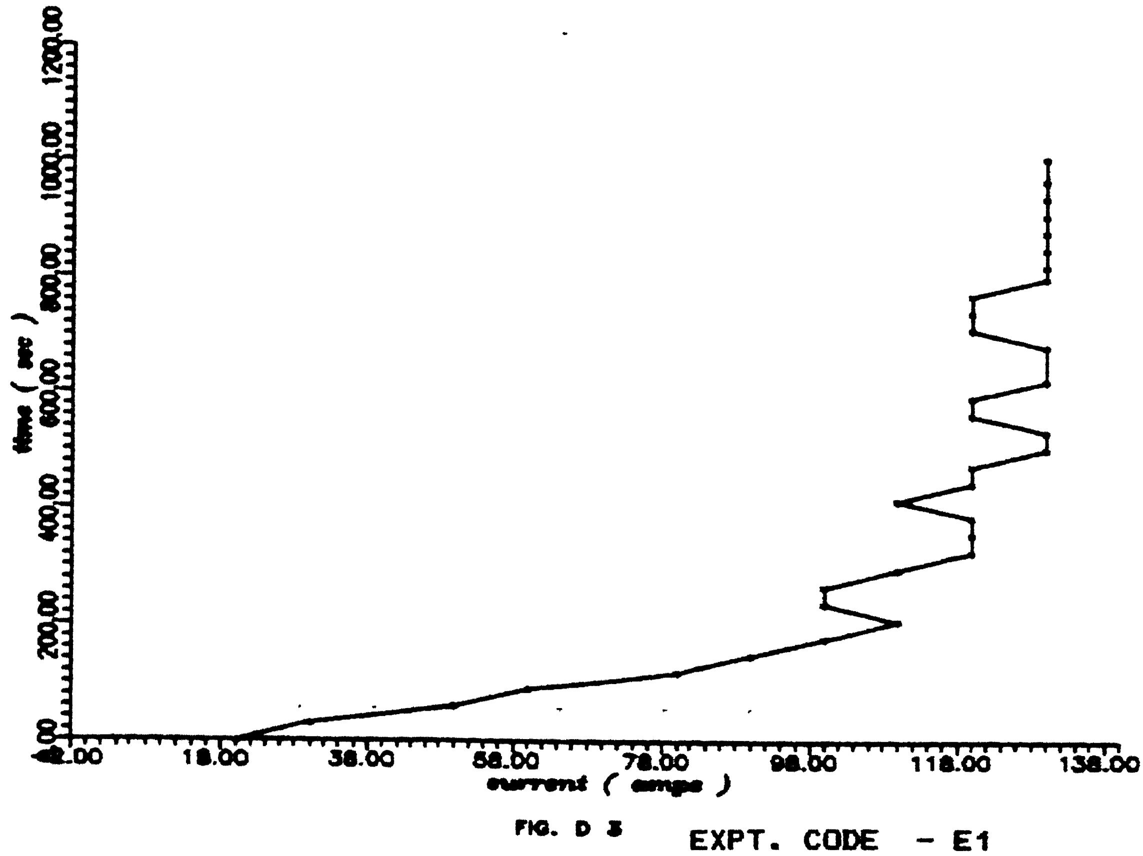


FIG. D 3

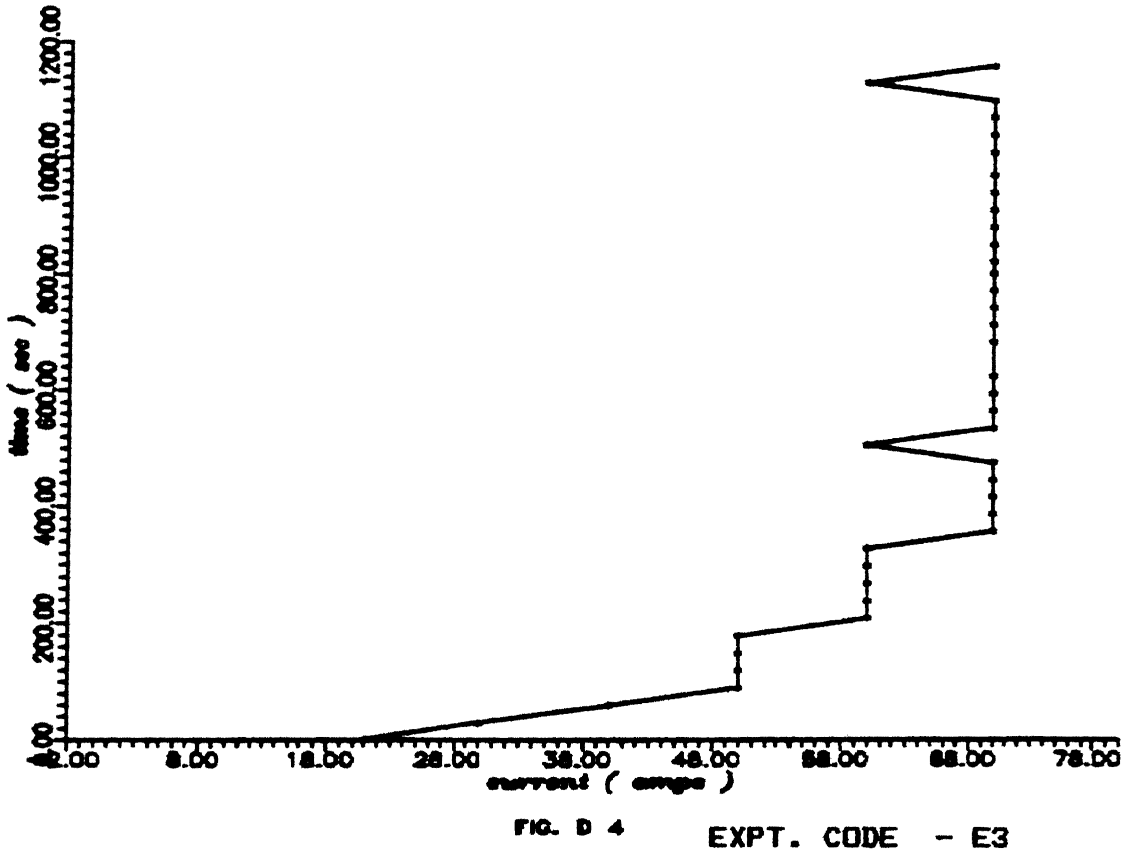


FIG. D 4

CURRENT HISTORY (CONVEX PROFILE TOOLS)

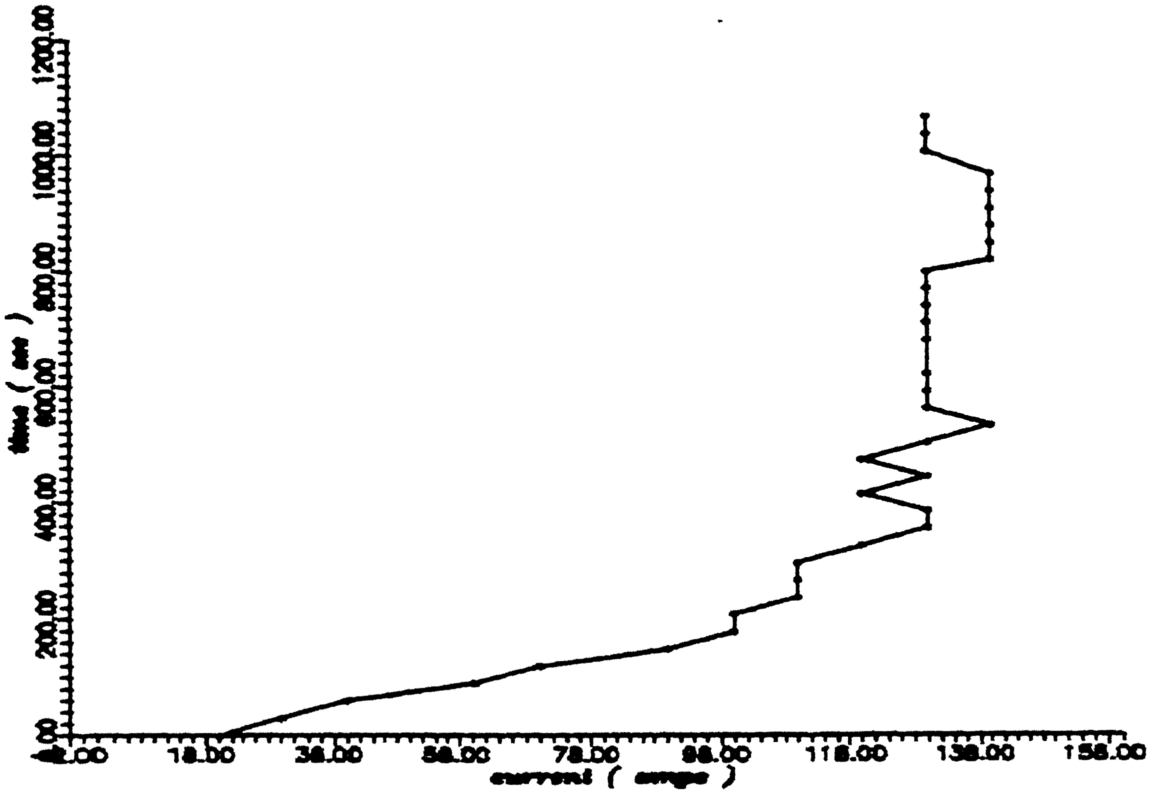


FIG. D 5 EXPT. CODE - E10

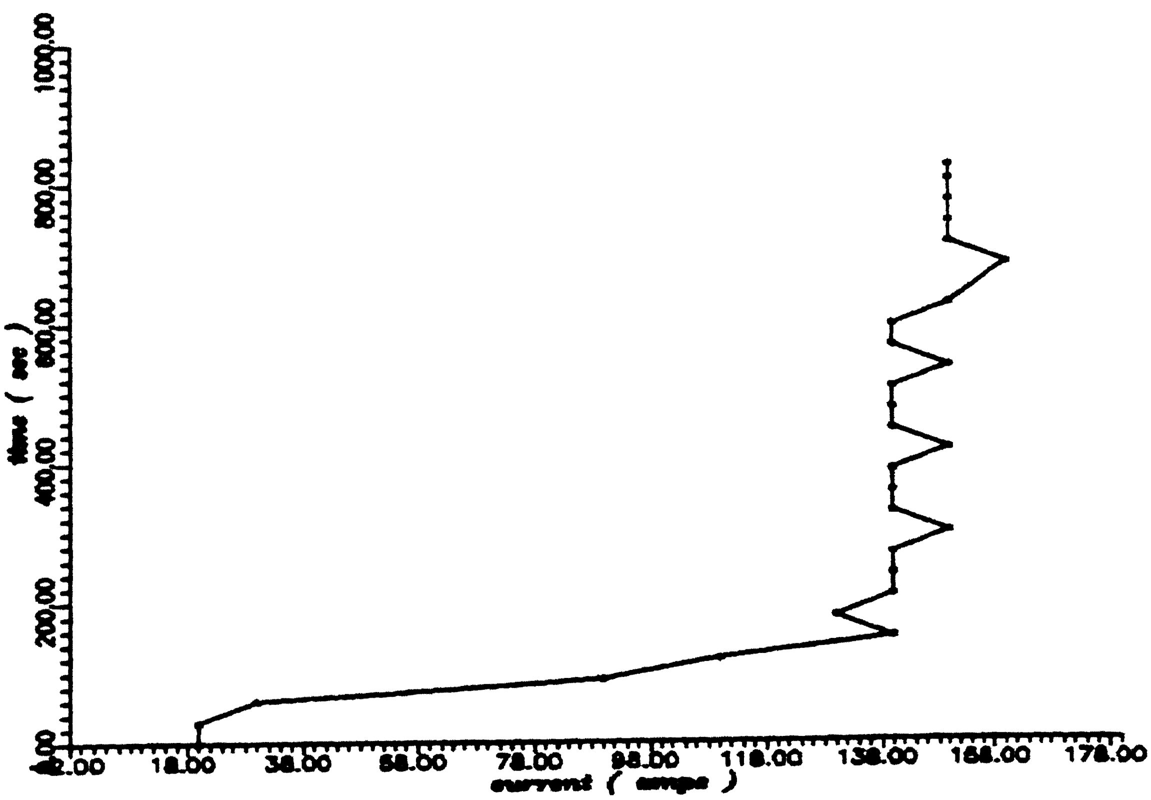


FIG. D 6 EXPT. CODE - C1

CURRENT HISTORY (CONVEX PROFILE TOOLS)

CHAPTER 4

CONCLUSIONS AND SCOPE FOR FUTURE WORK

4.1 Conclusions:

o A second order polynomial model adequately represents the relationship between ECD process parameters such as tool profile radius, input voltage and feed rate and the copied profile radius on the workpiece.

o The current history Tables 3.1..3.4 and graphs (Figs. C1..C6 and D1..D6) point to the fact that the processes have been relatively stable in experiments conducted with tools using convex profiles in comparison to the experiments conducted with concave profiles, which establishes that the pattern of flow of electrolyte after its exit from the tool tip influences the process and thus has a major role to play in the reproduction of profiles.

o The variation in the nature of the trends exhibited by the curves plotted for concave and convex profile tools also go to support the above statement.

4.2 Scope for Future Work:

o It is suggested that future work be undertaken to study the influence of flow pattern of the electrolyte which could be carried out by conducting experiments -

a) for conditions of perfectly blind holes.

b) with holes having few outlets on the sides (can be obtained by drilling holes on the side faces of the workpiece).

c) with holes having outlet at the base (can be obtained by

drilling holes on the top and bottom surfaces of the workpiece within the area of the leading face of the tool).

d) using rotating perforated tools.

o It is further suggested that the use of -

a) stepper motor for the feed mechanism be avoided in the experiments for future work and arrangements for continuous feed be incorporated to avoid its possible contribution to the instability of the process.

b) replica technique be avoided in future experiments for the measurement of radii of the copied profiles on the workpiece. One could however, go in for the measurement of radii, either by taking slices of the workpiece using softer materials to avoid difficulties in cutting out slices and preventing damage to the edges while cutting of the slices (since it is proved beyond doubt that the process is not affected by the physical and mechanical properties of the workpiece material) or by clamping together two similar, perfectly ground workpieces. (Only radius in one plane can be measured).

REFERENCES

1. Juneja, B.L. and Sekhon, G.S., "Fundamentals of Metal Cutting and Machine Tools," Wiley Eastern Ltd., New Delhi, 1987

2. Benedict, G.F.,"Non Traditional Manufacturing Processes," Marcel Dekker, Inc., New York, 1987

3. McGeough, J.A., "Advanced Methods of Machining," Chapman and Hall, London, 1988.

4. Debarr, A.E. and Oliver, D.A., "Electrochemical Machining," Macdonald and Co., Ltd.,London, 1968

5. Larsson, C.N. and Muzaffaruddin,K., "Electrochemical Effects on Shape Reproduction in ECM," 29th Int. MTDR Conf. Proceedings, 1978, pp. 533-540.

6. Kanetkar,Y., "Stray Current and Stagnation Zone Analysis in ECD During Outward Mode of Electrolyte Flow," M.Tech. Thesis, IIT Kanpur, 1987.

7. Adler Yu.P., Markava E.V., and Granousky Yn. V., "The Design of Experiments to Find Optimal Conditions," Mir Publishers, Moscow, 1975.

8. Cochran, W.G., and Cox., G.M., "Experimental Design," Asia Publishing House, 1977.

9. Bannard, J., "Fine Hole Drilling Using ECM," Proc. 19th International Machine Tool Design and Research Conference, 1980, pp. 503-510.

10.Cole, R. R. and Hopenfield, Y., "Investigations on Electrolytic Jet Polishing at High Current Densities," ASME Paper 62-WA-71,1962.

11.Loutrel,S.P. and Cook,N.H., "A Theoretical Model for High Rate ECM," Transactions of ASME, Journal of Engineering for Industry, 1973, pp. 1-6.

12.V. K. Jain, Vinod Kumar and P. C. Pandey, "Corner Reproduction Accuracy in Electrochemical Drilling of Blind Holes", Transactions of ASME, Journal of Engineering for Industry, Feb. 1984, Vol 106/55.

```
c program design of experiments

 double precision a(20,4),x(20,10),xt(10,20),xtx(10,10)
 double precision xtxi(10,10),xtxixt(10,20),b(10,1)
 double precision y(20,1),wkspce(10),z(1),h(20,10),c(10,20)
 double precision w(20,10),s(10),d(10,10)

 open(unit=21,file='doe.in')
 open(unit=22,file='doe.out')

 read(21,*)((a(i,j),j=1,4),i=1,20)

 do 10 i=1,20
        do 10 j=1,4
 x(i,j)=a(i,j)
  10 continue

 do 11 i=1,20
 x(i,5)=a(i,2)**2.
 x(i,6)=a(i,3)**2.
 x(i,7)=a(i,4)**2.
 x(i,8)=a(i,2)*a(i,3)
 x(i,9)=a(i,2)*a(i,4)
 x(i,10)=a(i,3)*a(i,4)
  11 continue

 do i = 1,20
 read(21,*)y(i,1)
 enddo

 call tpose(x,xt,20,10)

 call f01ckf(xtx,xt,x,10,10,20,z,1,1,0)
 call f01aaf(xtx,10,10,xtxi,10,wkspce,10)
 call f01ckf(xtxixt,xtxi,xt,10,20,10,z,1,1,0)
 call f01ckf(b,xtxixt,y,10,1,20,z,1,1,0)
C call f01ckf(d,xtxi,xtx,10,10,10,z,1,1,0)
```

```
 write(22,102)(b(i,1),i=1,10)
102 format(/1(f20.3))

 do 20 j=1,10
 do 21 i=1,20
 w(i,j)=x(i,j)*y(i,1)
  21 continue
  20 continue
C write(6,*)((w(i,j),j=1,10),i=1,20)

 do 27 j=1,10
 s(j)=0.0
 do 29 i=1,20
 s(j)=s(j)+w(i,j)
  29 continue
  27 continue
 write(22,205)(s(j),j=1,10)
205 format(//10x(f8.1))
 stop
 end


 subroutine tpose(h,c,m,n)
 double precision h(m,n),c(n,m)
 do 12 i=1,m
 do 12 j=1,n
 c(j,i)=h(i,j)
  12 continue
 return
 end
```